Carnegie Mellon University

CARNEGIE INSTITUTE OF TECHNOLOGY

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

TITLE: The Role of Uncertainty in Improving Fire Protection Regulation

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ACCEPTED BY THE DEPARTMENT OF: Engineering and Public Policy

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APPROVED BY THE COLLEGE COUNCIL:

____________________ DEAN ____________ DATE

Carnegie Mellon University

THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

A dissertation submitted to the Graduate School
In partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Engineering and Public Policy

By

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Pittsburgh, Pennsylvania
April, 2000

Acknowledgements

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) provided support for this work. I am indebted to Dr. Jack Snell, Laboratory Director, who mentored me and pointed me towards a degree in engineering with a broader societal focus. I thank the numerous BFRL staff who gave me advice and encouragement, particularly Dr. George Mulholland and Dr. Robert Chapman. I am indebted to Mr. Richard Peacock of the Fire Safety Systems Group of who wrote several of the programs to automate the data generation and analysis phases of this work.

I was so blessed with a dissertation committee strong in their respective fields and willing to lend their expertise to the study of fire safety. I am very grateful to my committee chair, Dr. Paul Fischbeck, who guided me through each step in the long process and spent many hours discussing fire safety regulations with me. Dr. Granger Morgan consistently challenged me to investigate the implications of my work to the many stakeholder groups, and Dr. Ardeshir Mahdavi, shared his expertise in building systems performance. I also send my heartfelt thanks to Dr. William Grosshandler, Chief of the Fire Science Division of BFRL who served on my committee and allowed me the freedom to pursue my ideas.

All my friends at Carnegie Mellon and in the greater fire protection community who listened to my ideas provided an invaluable support network. Dr. Indira Nair, who teaches a wonderful class in science, technology and ethics, helped me gain perspective on the societal implications of my work as well as perspective on my life. Jim Corbett, my dearest friend in the program, journeyed with me through all the highs and lows of graduate school and beyond.

I also want to thank my mom, she wrote and expressed to me that even though I did not chose to go to medical school, as she would have liked, she is excited that she can now call me "Dr." She is a terrific mom, very supportive and understanding. She is my role model in life and as I raise my daughter Alyssa.

I dedicate this work to my loving husband, Mike who moved to Pittsburgh with me for two years during which he was to make many sacrifices. Mike kept me going as he was always there with words of wisdom and a fresh way to look at things. Michael is a blessing in my life I thank him for all he has done.

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ABSTRACT

This dissertation defines an important role for uncertainty analysis in the adoption and implementation of improved fire protection regulations, both prescriptive and performance. It makes specific contributions to each of fifteen stakeholder groups who play a role in the conception, design, use, and maintenance of a building.

This dissertation promotes an understanding of the nature and sources of uncertainty, develops a common language among fire-safety professionals, and facilitates stakeholder discussions. Seven barriers to determining and documenting a level of fire safety for a given project are identified and the potential for switchover in the acceptability of a design is demonstrated. A taxonomy is created that is useful as a aid in understanding, identifying, and investigating uncertainties as a function of the steps in a fire safety-engineering calculation.

A generic methodology for the treatment of uncertainty in fire-safety engineering calculations is proposed. This methodology structures and quantifies many aspects of good engineering and policy analysis as applied to fire-safety engineering. The process developed is iterative and shows where effort should be made to treat complexity and where best-guess or average numbers can be used. Modifications to the current performance-based design process are suggested to provide for integration of uncertainty analysis.

Presentation of a case study shows the importance of a model that properly incorporates uncertainty over a traditional deterministic model. A model that handles the critical uncertainties is even more important as policymakers move toward a performance-based design context. Results of the case study provide insights useful for selecting design criteria, improving code language, and establishing research programs to support performance-based fire safety designs that ensure fire-safe buildings.

Through an evaluation of the cost-effectiveness of mandating residential fire sprinklers, this dissertation also demonstrates the value of properly incorporating variability and uncertainty in a cost-effectiveness and benefit-cost decision-making context. For the residential sprinkler problem, this was accomplished by discretizing national average values of fire statistics and costs by area of the country, community size, house type, and house age. This study shows that mandating residential fire sprinklers in new mobile homes can be cost-effective when compared to other residential life-saving options.

THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

1. Introduction

This dissertation defines an important role for uncertainty analysis in the adoption and implementation of improved fire protection regulations. Fire poses a significant societal risk and extracts a high cost. In an effort to reduce lives lost due to unwanted fires, many municipalities are passing legislation mandating the installation of residential fire sprinklers. Concurrently, in an effort to reduce the cost of providing for fire safe building construction, to stimulate innovation, and to increase design flexibility, many of the building and fire protection regulations around the world are being transformed from prescriptive-based regulations to performance-based regulations. However, implementation of any form of performance-based standards will require many decisions to be made. These decisions will be more difficult, more complex, and more uncertain than under a prescriptive-based code. Proper implementation of performance-based regulations for building fire safety requires a known confidence level in our ability to simulate fire in a building. The role of uncertainty analysis in the adoption and implementation of improved fire protection regulations is to address uncertainty in the application of our tools, direct our research and modeling efforts, guide code development, and facilitate cooperation among stakeholders by increasing the overall understanding of risks and costs.

1.1 Overview of the U.S. Fire Problem

1.1.1 Societal Risk and Cost

Fire poses a significant societal risk in the U.S. compared to other accidents and natural disasters. The civilian fire death toll for the period of 1989 to 1993 averaged 4,887 deaths/year. [*Hall*, 1996] In addition, firefighter deaths averaged approximately 100 deaths/year. Fires are one of the leading causes of accidental deaths, behind only vehicle accidents, falls, poisonings, and drowning. [*National Safety Council*, 1992 Edition] Each year, deaths from fire exceed the sum total of deaths from all natural disasters by an order of magnitude. Deaths from all natural disasters combined - floods, lightning, earthquakes, tornadoes, hurricanes, blizzards, and other storms total approximately 400 deaths/year. [*National Safety Council*, 1992 Edition] Likewise, annual direct dollar losses from all natural disasters combined average only a fraction of the annual direct dollar losses from fire, which totals over 8 billion dollars each year (in 1992 dollars). [*National Fire Data Center*, 1992] However, since most fires are relatively small, the cumulative impact of fire is not well recognized. The total loss from fire is significant, far more than the impressions many people have of it from the anecdotal reporting of local fires in the media.

1.1.2 Residential Fires

Residential fires only account for an average of 22 percent of the total number of fires each year. As shown in Figure 1-1, however, residential fires cause just over 80% of the total civilian fire deaths in the U.S. with highway vehicle fires causing 14.0% and non-residential fires causing only 4.0%. From the period of 1989 – 1993, the mean number of residential fire deaths per year was 3,910. [*Hall*, 1996]

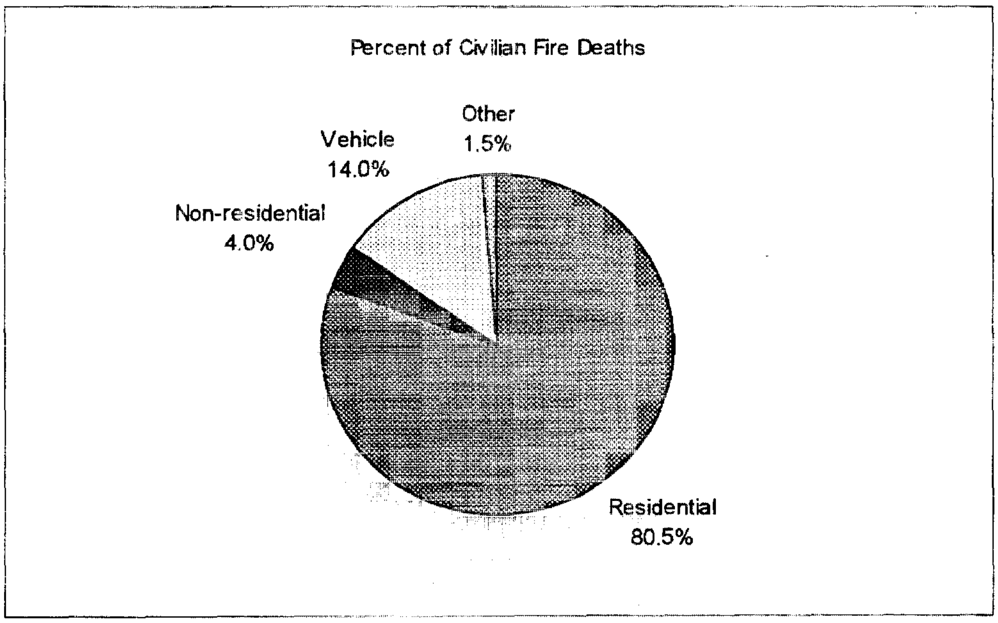

Figure 1-1. Percentage of Civilian Fire Deaths by Property Use

Residential fire injuries represent approximately 74 percent of the total civilian fire injuries per year. The mean number of U.S. civilian fire injuries over the period of study is 29,080 per year. Firefighter injuries in residential occupancies represent 57% of total firefighter injuries, with a mean of 57,100 per year. [*National Fire*

Data Center, 1992] Residential property losses accounted for an average of $4.3 billion dollars per year, or 53% of the total fire property damage. Thus, residential fires account for a large fraction of direct losses due to death, injury, and property.

Several studies have been conducted comparing U.S. fire statistics to those of other countries. The World Fire Statistics Centre in London publishes an annual report to the UN Working Party on Housing that focuses on comparison of the numbers. The UN report shows that the U.S. spends the most on fire-fighting organizations, 0.28% of GDP, and second highest on fire protection for buildings, 0.42% of GDP. Still, the U.S. has the third highest death rate of the countries reported,[i] over 5 times that of Switzerland which had the lowest death rate per 100,000 population. [*Wilmont*, 1995]

1.1.3 The Total Cost of Fire

The total cost of fire in the U.S. defined as the sum of the measures of loss caused by fire with what is spent to mitigate or prevent that loss has been estimated at $121 to $164 billion dollars. [*Hall*, 1998; *Meade*, 1991] Of this, less than 10% are economic losses. The growth in the total cost of fire has been led not by fire losses but by the other cost components.

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[i] The countries evaluated in order from lowest to highest death rates are: Switzerland, Netherlands, Austria, Spain, Germany, New Zealand, Czechoslovakia, France, Belgium, Japan, Sweden, Denmark, United Kingdom, Norway, Canada, U.S., Finland, and Hungary.

Table 1-1. Total Cost of Fire

Category	Cost (B $) 1995
CORE COSTS	
Economic Losses	11.3
Career Fire Departments	17.1
Net Fire Insurance	6.8
Building Construction For Fire Protection	**21.9**
NON-MARKET COSTS	
Human Losses (death and injury)	16.0
Value of Donated Volunteer Time	17-60
OTHER FIRE PROTECTION COSTS	
Cost Of Meeting Fire Grade Standards In The Manufacture of equipment	20.0
Costs of fire maintenance	7.3
Costs of fire retardants and all product testing associated with design for fire safety	2.8
Costs of disaster recovery plans	0.67
Costs of preparing and maintaining standards	0.22
GRAND TOTAL	**121-164**

The National Fire Protection Association states that since the early 1990's, the fastest rising component of total cost has been building construction for fire protection. [*Hall*, 1998] Most of the increases in construction costs occur because of regulation of commercial and industrial occupancies, thus raising the question of a need for less restrictive regulations and better optimization of safety and dollars spent on building fire safety construction.

1.2 The U.S. Fire Regulatory System

1.2.1 The Code Development Process

The U.S. has a complex system of building and fire codes and standards developed by multi-stakeholder committees. The codes are written by voluntary, "balanced" committees composed of a mixture of manufacturers, consultants, and special experts through a consensus process. These codes are prescriptive, specifying specific technologies and procedures for compliance based on generalized construction types and occupancy classifications. It has been noted that, over time, factors such as large loss fires, advances in technology, industry lobbying, and fear of liability have resulted in increases in the level of detail and number of code provisions. [*Meacham*, 2000] Codes are typically developed at the regional or national level; however, each municipality sets its own law by voting a particular version of a code or standard into law.

Key questions before the fire protection community today are: 1) Can the current fire codes be made less restrictive without compromising safety? 2) Are current fire safety standards in residences adequate to prevent loss of life? 3) Should all buildings within an occupancy classification be subject to the same fire safety regulations? 4) Are there areas where the fire safety performance of a given building could be met at lower cost by deviating from the prescribed code?

1.2.2 Performance-Based Building and Fire Regulations

The U.S. fire and building code system, following the lead of several other countries, is currently undergoing a regulatory transformation from a system of prescriptive codes to a performance-based system. Current building and fire codes in the U.S. are prescriptive. They specify fire protection requirements based on the construction of the building and its intended use. In contrast, performance-based standards specify the results, not the means, of regulatory compliance. The intent and motivation behind the reform effort is to reduce the total cost of fire by becoming more globally competitive, encouraging innovation, allowing for increased flexibility in design parameters, and providing a known level of risk.

Some economists believe that evolving regulatory policies now overwhelm government spending, tax, deficit, and monetary policies in determining U.S. unemployment, real income, and productivity. One researcher has tried to show quantitatively that increases in the amount of regulation correlate with negative macroeconomic trends. [*Goff*, 1996] Performance-based codes are in fact a reduction in the amount of regulation imposed and have become important in construction:

> It has been said by the Inter-jurisdictional Regulatory Collaboration Committee that, "The growing trend around the world to introduce performance-based codes is central to improving efficiency in the construction industry. In encouraging innovation and flexibility without strict prescription, performance-based building codes encourage new techniques and practices, leading to expansion and increased efficiency. This promotes investment in the industry,

> which in turn increases national GDP. [*Inter-jurisdictional Regulatory Collaboration Committee*, 1998]

This quote from the Inter-jurisdictional Regulatory Collaboration Committee hits upon the major motivations that countries cite for adopting performance-based codes and standards.

It has also been said that performance-based codes may lead to more effective policymaking because the debate focuses around the actual objective or risk. In a performance-based code, societal goals, design objectives, and performance requirements are explicit and open to public debate. Therefore, society's expectations of the level of safety provided in the buildings are part of the discussion. Under a prescriptive-based code, the discussion will more likely center on design-specific issues with no direct link to regulatory objectives.

For example, a lengthy discussion took place in the code development process over a proposed requirement for automatic fire sprinklers in patient sleeping rooms of hospitals. This discussion took place without any mention of a loss objective, an acceptable loss, a likely fire scenario, or potential losses with and without a detection system. A research project was initiated to develop technical information [*Notarianni*, 1993] but had to be conducted without an objective such as "save the people outside the room of origin," or "save the patient in the adjacent bed." Without such a clear objective, it is difficult to reach consensus on the level of fire protection needed.

1.2.3 Widespread International Adoption

Many countries including Australia, New Zealand, Great Britain, Japan, Finland, and Canada have published performance-based building and fire codes and many others are in the process of developing them. Australia published its national performance-based code in October 1996. [*Building Code of Australia*, 1996] The United States is drafting both a performance-based building and a performance-based fire code. These are scheduled for completion in 2000. Also, most of the other 500 or so U.S. fire codes published by the National Fire Protection Association are adapting performance-based alternatives to the current prescriptive codes. The Life-Safety Code, which covers issues of occupant safety in a variety of occupancy types, has a performance code option. [*NFPA*, 2000]

1.2.4 The Design-Performance Continuum

The distinction between performance standards and design standards is best characterized as a continuum. Regulatory policymaking usually involves selecting a point on a spectrum running from strict design standards to "pure" performance standards (that is, standards that give the least detail about what must be done to comply). In the early 1980's, a study was done to demonstrate applications of performance standards at various levels of regulation and to promote the adoption of performance-based codes.[*Project of Alternative Regulatory Approaches*, 1981] One of the issues highlighted in this study is that performance standards work well when actual performance can be evaluated and verified with a sufficient level of confidence. Because fire safety performance of a building is not easily measurable, the degree to which a performance-based fire safety design objective can be verified as meeting a predetermined societal objective is dependent on the technical predictive ability of the scientific tools, such as existing fire models. [*Brannigan and Lehner*, 1995] Thus, fire protection design would not be an obvious venue for performance-based standards. Performance standards should be adopted and implemented because of the potential advantages, but questions need to be addressed as to where on the continuum is optimum for fire safety regulations. To determine this, we need to know our ability to simulate fire conditions accurately, predict occupant response to fire, and determine toxic levels of products of combustion.

1.3 Simulation of Fire in a Building

Several publications conceptualize the implementation of a performance-based building and fire code system in the U.S. [*SFPE Task Group*, 1997; *Snell*, 1993] What is clear, although not explicitly stated, is that implementation of any form of a performance-based standard will require more decisions to be made. These decisions will be more difficult, more complex, and more uncertain than under a prescriptive-based code. It is challenging to make good fire protection decisions for a multitude of reasons such as poor loss statistics; incomplete and inadequate ability to model fire behavior; many players with competing objectives; the multi-disciplinary nature of the fire problem; the fragmented nature of the construction industry; non-technically trained building code officials; and our legal system.

Performance codes and standards work best when actual performance can be evaluated to determine compliance with a code. In fire safety, direct measurement of performance of a building or building systems is not usually possible. To test the fire safety performance of a building, a full-scale prototype of the building would have to be built and then burned under various scenarios. [*Brannigan and Smidts*, 1998] Even if this were not cost-prohibitive, it would be impossible to determine and to test all possible fire scenarios.

Thus, the quality of the performance-based design is directly a function of what can be termed "technical predictive ability." Technical predictive ability has been defined as the ability to predict the performance of a building subject to a variety of statistically valid fires with sufficient accuracy to allow the building to be deemed to meet the performance objectives.

Fire science is in its infancy in terms of being able to calculate the behavior of fire in a building. Calculation procedures and empirical equations have been developed to predict parameters such as burning rates, release rates, and rates of generation of products of combustion. These are vital inputs to fire models, which calculate the build-up and spread of heat and gases in the building, the time to activation of fire protection devices such as smoke detectors and sprinklers, and the time available for safe egress from the building. Also, many human response phenomena such as response to a fire alarm must be simulated.

Uncertainty exists around the use of these calculation methodologies and fire models. Most were developed by researchers to explain fire behavior observed during controlled laboratory tests. Many have limitations that are poorly understood. An engineering and scientific evaluation of the state-of-the-art of predictive tools is needed to identify the important technical issues. Ultimately, integration of our building and fire safety standards with scientifically-based engineering methods is needed in order to advance fire-safety design practice significantly.

1.4 Role of Uncertainty in Fire Calculations and Fire Policy

Uncertainty plays a major role in all aspects of a performance-based design. There is uncertainty in the model physics, uncertainly in the input values to the model, uncertainty in people's values when it comes to fire safety, and uncertainty in human behavioral responses to fire. Identification, characterization, and a rigorous methodology are needed to handle these uncertainties. The methodology must address the needs of designers, code officials, code developers, policy makers, and researchers. Accounting for unknowns and variations is necessary in performance-based designs to provide confidence in the final design.

Currently, there is no accepted method with which to treat uncertainty in fire protection engineering design. The need to account for safety and reliability in calculation protocols is discussed at the first international conference on Performance-based codes and fire-safety design methods. [*Lucht*, 1996] Uncertainty is usually ignored or treated poorly. Often, factor-of-safety methods are proposed which are based on historically derived safety factors. However, these do not work well for a performance-based design, because derivation of a safety factor is dependent on prior experience. As new technology, innovative applications, and deviations from the prescriptive code become more common, historically derived safety factors will be less available and less applicable. Therefore is important for the engineer to understand not only the theory behind uncertainty analysis but also how to apply it to a complex fire protection engineering design.

Furthermore, it is impractical to include treatment of all uncertainties in a performance calculation. It should be determined if a given uncertainty is of statistical and/or scientific importance. Only uncertainties that are important to the physical outcome of interest should be treated quantitatively in these analyses. A methodology is needed that is sufficiently rigorous to identify these uncertainties. It must be developed by someone with an understanding of the underlying physics in the fire models and other technical tools.

1.5 Outline Of Dissertation And Discussion Of Customers

Chapter 1 defines an important role for uncertainty analysis in the adoption and implementation of improved fire safety regulations, both prescriptive- and performance-based. Because uncertainty is a broad and general term used to describe a variety of concepts, Chapter 2 explores these concepts and the nature and sources of uncertainty in fire protection engineering. Also in Chapter 2, the performance-based design process is reviewed, and several barriers to determining and documenting agreed upon levels of fire safety are identified. The problem of switchover, where variations in analysis parameters, assumptions, or model inputs cause changes in the acceptability of the final design, is introduced. The problems with conducting an uncertainty analysis are discussed, and a taxonomy useful in structuring a framework for understanding, identifying, and investigating uncertainties as a function of the steps in a fire safety engineering calculation is developed.

Chapter 3 suggests a quantitative methodology for the treatment of uncertainty in fire safety engineering design calculations that is comprehendible but rigorous. It breaks the process of conducting an engineering design calculation down into identifiable steps, each of which can be expanded or contracted to fit a specific design problem. Chapter 4 demonstrates the application of the methodology to a case study of an actual building. Chapter 5 presents the results of the case study and demonstrates how uncertainty analysis can be used to create distributions of key outcome criteria, estimate time to untenability, judge acceptability of egress time, and compare two designs. It is also shown how results of the uncertainty analysis can be used to determine the uncertainty importance of the input parameters and to simplify future uncertainty analyses. Chapter 6 demonstrates how uncertainties in fire protection are treated in a benefit-cost study of a residential fire sprinkler regulation and discusses the insights obtained.

This work is meaningful to many stakeholder groups. Conclusions and recommendations to stakeholder groups are presented in Chapter 7. The methodology defines and standardizes a process for design engineers to follow in order to quantify the level of confidence in the final design. It makes explicit the consideration of many "what if" scenarios typically of concern to the authority having jurisdiction. It provides building owners with a way to compare quantitatively the level of safety and the cost of various fire protection designs. It provides for life-cycle safety of the building and, thus, will lead to increased public safety. It demonstrates to researchers how best to prioritize enhancements to the physics and structure of fire models and provides insights to policy makers and code developers who are drafting new regulations. Most importantly, it provides for the facilitation of open discussion among the stakeholder of the risks, costs, and benefits of any given option.

1.6 Chapter 1. References

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THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

2. UNDERSTANDING AND IDENTIFYING UNCERTAINTY IN FIRE-PROTECTION ENGINEERING DESIGN

Uncertainty is a broad and general term used to describe a variety of concepts including but not limited to lack of knowledge, variability, randomness, indeterminacy, judgement, approximation, linguistic imprecision, error, and significance. These and many other facets of uncertainty are discussed in more detail in Chapter 4 of *Uncertainty* [*Morgan and Henrion*, 1990]. The variety of types and sources of uncertainty, along with the absence of agreed upon terminology, generates considerable confusion in the fire protection engineering world. Many facets of uncertainty can be understood through statistical and scientific concepts, some of which are presented below. However, uncertainties in the engineering design process, such as those surrounding the selection of performance criteria, are best understood by their ability to change the acceptability of a design. Finally, to understand uncertainty in fire safety engineering fully, one must be cognizant of the difficulties in conducting a complete uncertainty analysis.

2.1 Nature and Sources of Uncertainty

Uncertainty is often discussed as though it was synonymous with measurement uncertainty, i.e., doubt about the validity of the result of a measurement. Measurement uncertainties are characterized from both a statistical analysis of a series of observations (to determine the random error) and from systematic effects associated with corrections and reference standards (to determine the systematic error). The total error is defined as a combination of random and systematic errors. Much work has been done to reach an international consensus on the evaluation and expression of measurement uncertainty. General rules for evaluating and expressing uncertainty in measurement are provided in a guide published by the American National Standards Institute and the National Conference of Standards Laboratories [*American National Standards Institute*, 1997]. An example of dealing with measurement uncertainty in fire protection engineering is found in a study of the uncertainty surrounding the use of thermocouples to measure temperature [*Pitts et al.*, 1998].

However, uncertainty also arises from a variety of other sources to which standard techniques for the evaluation and expression of uncertainty do not always apply. Uncertainty can arise from a *lack of complete knowledge.* What is the heat release rate or radiative fraction of a mixed-fuel package? We have not measured and cannot reliably predict the value of these quantities for all potential fuel packages. Furthermore, the heat release rate and radiative fraction vary with parameters such as geometry, source and strength of ignition, and ventilation conditions. Uncertainty may arise from *randomness* such as where and how the fire will start. Uncertainty may arise from *indeterminacy,* the inability to know what will happen in the future. For example, the occupancy of and furnishings in a building may be different ten or twenty years after it is built. Uncertainty may arise due to the *unpredictability of human behavior.* It is unknown what actions each occupant will take upon discovering a fire or hearing an alarm. Uncertainty can arise because of *disagreement between information sources*. Rates of generation of products of combustion per gram of fuel burned vary from study to study and even from test to test in the same study using the same instruments.

Uncertainty may arise from *difficulties in defining the problem*. For example, a goal may be established to provide an equivalent level of fire safety. However, equivalency may be defined as providing the same time available for egress, providing the same level of property protection, providing the same level of fire safety for fire fighters entering the building, or all of the above. Uncertainty may also arise from *linguistic imprecision*. It is difficult to determine what exactly is meant by "flame spread should be limited." While this is true, these sources can usually be removed via proper problem definition. Uncertainty often refers *to variability*. For example, the ambient temperature and the total number of deaths from fire can vary in time by season, month, and day. They also vary by region of the country and community size. Even if we had complete information, we may be uncertain because of *simplifications and approximations* introduced due to *computational limitations*.

Custer and Meacham discuss uncertainties inherent in the performance-based analysis and design process in Chapter 9 of *Introduction to Performance-Based Fire Safety* [*Custer and Meacham*, 1997]. The authors pose questions related to understanding uncertainties in risk perceptions, attitudes, and values. As

Morgan and Henrion point out, "In addition to being uncertain about what exists in the external world, we may be uncertain about individual preferences, uncertain about decisions relating to potential solutions, and even uncertain about the level and significance of our uncertainty." Understanding the level and significance of our uncertainty is crucial to making good fire safety design decisions.

2.2 Uncertainties in the Design Process and The Problem of Switchover

Of practical significance is that direct measurement of the fire safety performance of a building or building system is not usually possible; therefore, we must rely on the technical predictive ability of scientific tools such as existing fire models. The problem is that numerous uncertainties in the application of these fire safety design tools often go unrecognized or ignored. Many of these uncertainties are inherent in the design process itself. Variations in analysis parameters, assumptions, or model inputs may cause output criteria to change. *Switchover* occurs when outcome criteria change enough so as to cause a change in the design decision, (e.g., the acceptability of a final design). It is critical to know if different sets of reasonable inputs, scenarios, or parameters used in a fire safety engineering design have the potential to cause switchover and lead to different acceptable designs.

The Society of Fire Protection Engineers (SFPE) *Engineering Guide to Performance-Based Fire-Protection Analysis and Design of Buildings* details several steps in the design process [*SFPE*, 1999]. As shown in Figure 1, adopted from the SFPE Engineering Guide. The stated intent of the guide is to "provide guidance that can be used by both design engineers and approving authorities as means to determine and *document achievement of agreed upon levels of fire safety* for a particular project."

A review and analysis of the performance-based design process for fire safety engineering outlined in the guide along with a review of several case studies of performance-based, fire safety engineering designs for actual buildings was conducted [*Notarianni and Fischbeck*, 1999]. This review uncovered seven major barriers to determining and documenting achievement of agreed upon levels of fire safety for a particular project. All seven barriers involve various types of uncertainty. Thus, there is a well-defined and strong role for uncertainty analysis in improving the ability to document achievement of agreed upon levels of fire safety. The seven barriers identified are presented below along with a discussion of how they might lead to switchover of a design from acceptable to unacceptable.

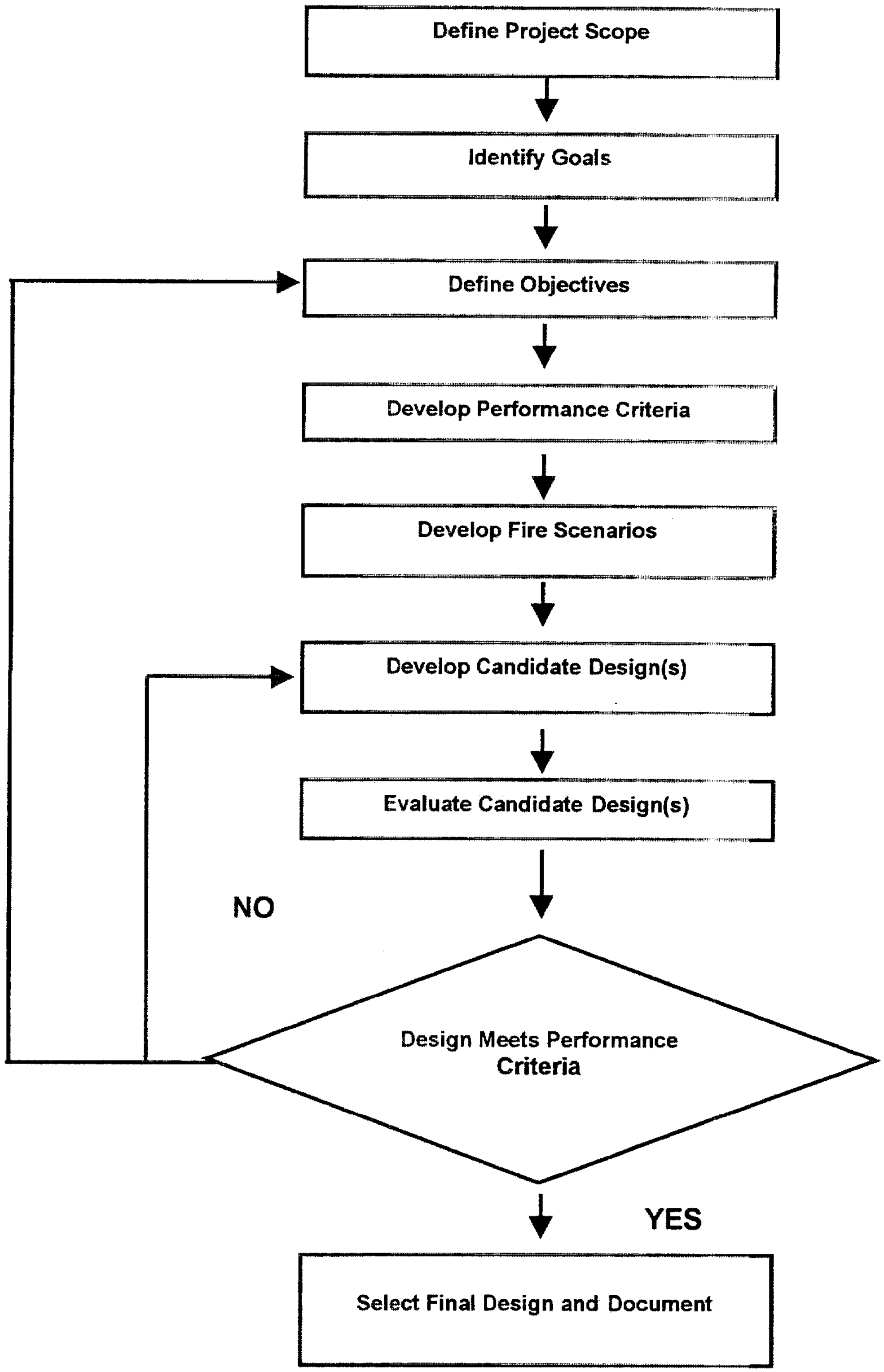

Figure 2-1. Overview Of The Performance Based Design

2.2.1 Performance Criteria Are Not Established

There is uncertainty in the *selection of performance criteria*. In fact, performance criteria have not been established or agreed upon by the fire safety community, and current policy allows the stakeholders themselves to select the criteria to be used for each design. Discussions occur around such questions as: Is the set of performance criteria sufficient? What do the numerical values actually represent? Should different criteria be used with different sub-populations such as the sick, the elderly, or the handicapped? At one recent international conference, two engineers presented their performance-based case studies conducted for real clients on actual buildings. They had each followed the current design guidelines; however, they had selected very different performance criteria [*Stroup*, 1998; *Sullivan*, 1998]. Differences existed on three levels: 1) the parameters included in the set of performance criteria, 2) numerical values selected as the critical or cut-off values for these parameters, and 3) the presence or absence of a time element for reaching the cut-off values. Since predictions of fire models are compared to selected performance/life-safety criteria in order to determine if a design is acceptable, variations in criteria can cause the same design to pass or fail.

2.2.2 The Design-Fire Selection Process Is Unspecified

Design fires are defined fire challenges (e.g., a grease fire on the stove, a smoldering cigarette fire on the sofa). Along with design fires, several fire scenarios, or descriptions of possible fire events that could occur are developed. For each design fire evaluated, the goal is to provide a fire-safety design that would satisfactorily mitigate unwanted fire scenarios from developing.

Because it is impossible to evaluate physically the performance of building systems in response to all design fire scenarios that might occur, how can one have confidence that the design fires and resulting fire scenarios represent the range of fires that might occur in the building? Usually a designer will try to select "worst-case" or "reasonable worst-case" scenarios. However, which scenarios present a worst-case situation or how likely (or unlikely) a particular scenario is may not be intuitive. It is debatable whether we should be designing for the one-in-a-million fire and how many design fires and fire scenarios are sufficient. A methodology is needed that would incorporate the likelihood of a design fire and/or associated design fire scenario. It is easy to see how the same design may be deemed acceptable if based on a limited number and type of design fires or deemed unacceptable if based on an expanded set of scenarios or an unrealistically pessimistic set of scenarios.

2.2.3 Assumptions Are Made About Human Behaviors In Fire

During several critical steps in the design process, *assumptions are made about human behaviors in fire*. For example, some egress models used by fire-protection engineers to predict the time required for safely evacuating a building (or part of a building) make many assumptions about how humans behave. Two of the stated assumptions built into one internationally used egress model are 1) 100% of the occupants are readily mobile and 2) occupants begin leaving the building immediately upon hearing an alarm [*Portier et al.*, 1996]. Experience demonstrates that this is often not the case, see for example, [*Benthorn and Frantzich*, 1998; *Proulx*, 1998].

Other behavior assumptions may not be explicitly stated but can be inferred from an analysis of model outputs. For example, results from a recently published study of a performance calculation using the egress model in FASTlite reveal that assumptions are made about human behavior during fires [*Portier et al.*, 1996]. A decrease in the number of exits by 1/3 increases the egress time by exactly 1/3. This suggests an implied assumption that an equal number of people egress through each available exit. More typically, actual human behavior will be to exit following the path one normally uses to enter and exit the building. Existing egress calculations and models need to be evaluated so that unrecognized and/or unstated uncertainties resulting from assumptions regarding human behavior can be identified. Once revealed, the implications of these assumptions need to be explored quantitatively.

2.2.4 Predictive Fire Models Have Limitations That Are Not Well Documented Or Widely Understood

Fire models and other calculation methodologies are often inappropriately used to develop and evaluate candidate designs for buildings and/or scenarios outside of the models predictive capabilities. This occurs because *limitations of fire* *models are not well documented or widely understood.* For example, computer fire models do not model fire directly and only predict fire effects based on user selected input data. Because many existing fire-model and calculation methodologies were originally developed as research tools, model conditions, defined as "fundamental requirements for the model's validity, "[*Brannigan and Smidts*, 1998] are often unknown or unstated. Estimates provided by a model are technically credible only when model conditions have not been violated.

2.2.5 Outputs Of Fire Model Are Point Values That Do Not Directly Incorporate Uncertainty

Even when the model is used within its intended limitations, *fire-model outputs are point values* that do not reflect inherent input uncertainties (e.g., fire growth rates, initial conditions). Without knowledge of the uncertainty surrounding a prediction, it is impossible to be certain of a design's acceptability. One example is the response of fire-protection equipment such as sprinklers, heat detectors, and smoke detectors. Predictions of the time to activation of such devices would specify for example, 121 seconds. However, the actual time to activation may be higher or lower depending on any factors not modeled including individual detector characteristics and distance below the ceiling.

2.2.6 The Design Process Often Requires Engineers To Work Beyond Their Areas Of Expertise

Problems can also occur when *fire-protection engineers are required to work in domains outside their expertise*. "Conservative" assumptions made by wellintentioned engineers may not be as conservative as intended. For example, a design engineer intending to be "conservative" may assume that tenability would be violated when any one of a set of individual criteria such as temperature or carbon monoxide exceeded its minimum value. However, toxicity experts might argue that temperature and gas interactions cause tenability to be violated even when each of the individual species are in "acceptable" ranges. Likewise, a design engineer may assume that the time to react to an alarm for a resident is "conservatively" set equal to the travel time needed to go from one remote corner of the unit to the other most remote corner of the same unit. However, this may not be that conservative since even a fully ambulatory occupant may stop to gather belongings, rescue a pet, call a neighbor, etc.

2.2.7 No Standardized Methods Exist To Incorporate Reliability Of Systems

The last barrier identified is the *uncertainty surrounding both the reliability of a given fire-protection device/system/or characteristic and the lack of standardized methods to incorporate reliability* into performance-based engineering calculations and decisions based upon these calculations. For example, we may be uncertain about the reliability of a given fire suppression system. Sometimes a fire suppression system is proposed as an alternative to passive fire protection such as compartmentalization. However, these two alternatives have different reliabilities. There is no universally agreed upon methodology that describes how to account for these differences.

These seven barriers to determining and documenting achievement of agreed upon levels of fire safety for a particular project must be addressed fully in order for all stakeholders to have a known level of confidence in the science-based predictions and the resulting final design. All seven barriers involve various types of uncertainty. Thus, there is a well-defined and important role for uncertainty analysis in fire safety-engineering calculations. Although this clear role for uncertainty in improving the development and implementation of performance-based fire safety regulations exists, uncertainty analysis is clearly an uncomfortable topic for many of the stakeholders in the process.

2.3 Difficulties with Conducting Uncertainty Analyses

Discussion of the proper treatment of uncertainty in a fire safety engineering calculation is difficult for several reasons:

1) *The magnitude of the problem is not clearly understood.* It is widely assumed that a mixture of "conservative assumptions" and "factors of safety" can be used to "cover for" uncertainties. However, factors of safety that are applied at various stages of the analysis are not necessarily linearly related to the critical output parameters, potentially resulting in a reduced (or no) factor of safety in the results.
2) *There are many types of uncertainties that go unrecognized or ignored.* These include uncertainties in variables "hard-wired" in the scientific tools,

uncertainties in tenability/performance criteria, uncertainties surrounding the selection of design fires, and uncertainties in human behaviors and values.

3) *Fear of the effect on the implementation of performance-based regulations.* There is a fear that identification and treatment of uncertainty would show that our current ability to predict the build-up of heat and toxic products of combustion is not accurate enough to judge the acceptability of a proposed design with a high enough confidence level. This would delay implementation of the entire performance process until predictions of critical outcome criteria can be more certain.
4) *No quantitative methodology exists for treating uncertainty in performance-based designs.* A methodology is needed that is both rigorous and comprehendible.
5) *Impracticality.* Fear that the mathematical rigor needed to conduct such an analysis would render the process impractical.
6) *Paucity of data.* To quantify uncertainty adequately, a large quantity of data would be needed to determine ranges of values for input parameters such as heats of combustion, rates of production of various gaseous species, and other important inputs. A large quantity of data would also be needed to validate predicted values with empirical data from real burn scenarios.

It should be pointed out that these are real and valid concerns due to the combination of poorly defined and unstructured problems and the lack of a user-friendly methodology. Current common practice for doing "uncertainty" analyses involves completing a series of single-variable sensitivity studies. Application of these techniques to a complete performance-based design containing hundreds of variables is impractical. The following sections focus on practical ways to identify and account for uncertainties in fire-protection engineering design.

2.4 Identifying Uncertainties In Fire Protection Engineering

When considering uncertainty in a fire-protection engineering calculation, fire-protection engineers typically consider first the uncertainties associated with the calculation inputs, usually empirically measured quantities such as heat release rates. However, there are many other types of uncertainty integral to fire-safety engineering design. Custer and Meacham identified many of these in *Introduction To Performance-Based Fire Safety* [*Custer and Meacham*, 1997].

In a complete uncertainty analysis, not all uncertain parameters need to be treated quantitatively, only parameters or combinations of parameters with the potential to cause switchover in the final decision on the acceptability of a design. Other uncertainties which have minimal effect on the results can be ignored, and best-guess values of these parameters can be used in the calculations. Still others, such as societal values become policy or regulatory issues and should be treated parametrically to allow decision makers to see the effects of alternative choices. The intelligent use of safety factors can often cover more than one type of uncertainty. Still, it is useful to first identify sources and types of uncertainty from a broad perspective. Without first adequately identifying the sources of uncertainty, we cannot understand how to best handle them.

Section 2.4 presents a taxonomy useful in developing a framework for understanding, identifying, and investigating uncertainties as a function of the steps in a fire-safety engineering calculation. The taxonomy builds upon earlier work presented at a conference on Fire Safety Design in the 21st Century [*Notarianni and Fischbeck*, 1999].

2.4.1 Scientific Uncertainties

Scientific uncertainties are due both to lack of knowledge (e.g., in the underlying physics, chemistry, fluid mechanics and/or heat transfer of the fire process) and to necessary approximations required for operational practicality of a model or calculation. Of the many types of uncertainty found in performance-based fire-safety design calculations, scientific uncertainties are typically the most easily recognizable and quantifiable. The many types of scientific uncertainty can be roughly divided into five sub-categories: 1) theory and model uncertainties; 2) data and input uncertainties; 3) calculation limitations; 4) level of detail of the model; and 5) representativeness of the design-fire scenarios.

Theory and model uncertainties arise when physical processes are not modeled due to lack of knowledge of how to include them, processes are modeled based on empirically derived correlations, and/or the making of simplifying assumptions.

These types of uncertainties are present in all compartment fire models, in which each of these factors leads to uncertainties in the results. Most compartment fire models are zone models, which make the simplifying assumption that each room can be divided into two volumes or layers, each of which is assumed to be internally uniform and that changes in energy or compositions are implemented immediately throughout the layers. Current zone models do not contain a combustion model to predict fire growth, forcing the model user to account for any interactions between the fire and the pyrolysis rate. Many compartment fire models also use an empirical correlation to determine the amount of mass moved between the layers.

Data and input uncertainties arise from both lack of knowledge of specific input values and variations in input values as a function of many factors such as time, temperature, and region of the country. For example, the rate of heat release of a three-cushion upholstered sofa may be uncertain due to lack of available data for sofas with the same dimensions, stuffing, and cover materials. Results also may be uncertain because the test method by which the heat release rate was measured could not specify all combinations of ignition source and strength and because there are inaccuracies inherent in the instrumentation used in the test. Other inputs such as concentrations of toxic gases produced vary with time as the fire develops and are uncertain. The species production constants used to predict concentrations are a function of the material or combination of materials actually burned. This is unknown *a priori* to the design stage.

For most fire models and calculation procedures, very different answers can result depending on the *calculation limitations*, control volume selected for modeling, the *level of detail of the model*, and the model-domain parameters specified. Model-domain parameters set the scope of the system being modeled and define the model's level of detail and/or base-line properties. Though these parameters or quantities are often ignored during uncertainty analysis, they have the potential for considerable impact [*Morgan and Henrion*, 1990]. This has been shown for fires in high-bay spaces. Differences in the outcome criteria such as maximum temperature and time to activation of fire detectors and sprinklers are found when a large space is modeled with a simple zone fire model versus a more detailed computational fluid dynamics model [*Notarianni and Davis*, 1993]. Differences in the outcome criteria are also found when a large space, which is typically sub-divided by draft curtains,[i] is modeled. If a control volume is drawn around a single draft curtained area (as opposed to drawing the control volume around multiple draft-curtained areas or around the entire building), higher temperatures and faster activation times of installed fire-protection devices will be predicted. Also, significant to the uncertainty in the outcome parameters are the index variables of the model. Index variables are used to identify a location in the domain of a model or to make calculations specific to a population, geographic region, etc.

[i] A draft curtain is a barrier that extends a certain vertical distance down from the roof or ceiling. Draft curtains are installed to sub-divide a large area with the intent of corralling heat and smoke.

Uncertainty arises in both the *number and type of design fire scenarios* that need to be modeled for a given design/building. There may be significant differences between reality and the design fire scenarios that were used to judge the adequacy of the performance-based design. Variations in the ignition source, rate of growth, and/or the materials burned affect confidence in the results. It is unclear if all statistically significant fire scenarios should be modeled or if worst-case or reasonable worst-case scenarios are adequate. Furthermore, a worst-case scenario may be defined in terms of many different variables. A scenario may be worst-case because it is most likely to cause death, because it has potential for large property loss, or for other reasons.

2.4.2 Uncertainties and Variability in Behavior

Human behavioral uncertainties concern both the way in which people act in a fire and how these actions should be considered during steps in the design process (e.g., definition of project goals, selection of performance criteria, and development and evaluation of candidate designs). Behavioral scientists tell us that human actions can range from somewhat predictable to unpredictable. Actions are more predictable when choices are limited, procedures are practiced, the situation is not novel, and little chaos is present. Unfortunately, during a typical fire, few if any of these conditions occur. Brannigan discusses what he calls "intentional uncertainty" in relationship to human behavior [*Brannigan and Smidts*, 1998]. Brannigan states, "human decision making does not follow the same kind of well understood rules that control the physical science variables used in models. Human decisions represent intentional uncertainty."

For example, human behavior in *response to a fire alarm* must be modeled in terms of time to respond to the alarm and type of response. Does the person immediately begin to evacuate the building? Does he/she take the stairs or the elevator? What factors enter into that choice? Does the person try to fight the fire? Does the person stop to gather personal possessions or call a neighbor? Another area of human behavior relevant to performance-based calculations is *behavior during egress*. Do people use the best exit or the most familiar one? How long do people take to start to exit?

Human factors also affect the analysis needed for *identifying goals and objectives and developing performance criteria*. Fire-safety goals typically include levels of protection for people, with performance criteria being a further refinement of these objectives. Performance criteria are numerical values to which the expected performance of candidate designs can be compared. What range of occupant characteristics such as age and handicaps should be considered? How do human behaviors such as behavior during egress influence the numerical values chosen for performance criteria?

When developing and evaluating candidate designs, the efficacy of the proposed fire-safety measures mitigating all likely fire scenarios should be determined. This involves varying human behavioral elements. For instance, two very different fire scenarios could develop from the same cooking-initiated design fire: 1) a grease fire from cooking sets off a smoke detector that alerts the occupant who reacts and properly extinguishes the fire while it is still small; or 2) the occupant forgets and leaves a pot simmering on a burner, takes a sleeping aid, and goes to bed. The overheated pot ignites and the fire spreads to one or more adjacent items.

2.4.3 Uncertainties and Variability in Risk Perceptions and Values

There is both *variability and uncertainty in the way people perceive and value risk*. Capturing differences that people have in their perceptions and values related to risk is a necessary step in the design process. Research has shown that though people typically view consequences from voluntary risks less severely than equal consequences resulting from an unknown and/or involuntary risk, there is variability [*Starr*, 1969]. For example, while some people would agree that an increase in risk to fire fighters (people who accept risk as part of their job) is justifiable if a corresponding decrease in risk to the public could be achieved, others would not. Few studies have been conducted that clearly demonstrate how society values fire-safety risks at the level needed to support performance-based trade-offs. Some work on incorporating risk concepts and identifying levels of acceptable risk is discussed in [*Meacham*, 2000]. It is important to identify where value judgements enter into a performance-based calculation and to make any assumptions explicit regarding values and the impact of different values on the final design.

Another important factor is the concept of *equivalency*. Equivalency can mean different things to different stakeholders. For example, one person may determine that non-combustible construction is equivalent to an installed sprinkler system if they are both shown to both provide for time to egress the building. Another may argue that they are not equivalent, because the reliability of the sprinkler system is less. Designs may be equivalent in terms of life safety, property protection, business interruption, injuries, and/or prevention of structural collapse, but they are most likely not equivalent in all regards. It is, therefore, important to make explicit what assumptions "equivalency" is dependent upon?

2.4.4 Uncertainties Related to the Life-Cycle Use and Safety of Buildings

Many factors change over the lifetime of a building. The uncertainties surrounding future use, occupancy, and other factors contribute to the difficulty in conducting a structured performance-based design. Even daily fluctuations in these design parameters can affect the safety of a building. For example, a building or area of a building that is normally occupied 24-hours/day may become unoccupied (or occupied by very different people) for extended periods of time due to extraneous factors (e.g., business closing, maintenance, renovation). The characteristics of the different occupants such as the elderly or the handicapped can lead to very different design considerations. Other changes that may affect the life-cycle safety of the building are fire-service characteristics such as distance of the building to the nearest firehouse, and expected response time of the fire department.

2.4.5 Uncertainties Related to Providing for Equity and Incorporation of Societal Values

This involves determining what is important to the stakeholders and to what degree protection should be provided. A mechanism should be provided to assure equal outcomes for sub-groups. Since in most projects there are many stakeholders such as the building owner, design engineer, architect, code official, and the public (users of the building), it is difficult to assign worth in the usefulness or importance of something and apply it across all individual and societal issues. The key here is that decisions that change if a value, attitude, or risk perception varies must be made explicit in the design. Agreement on these key decisions by all stakeholders is critical to the success of a performance-based design.

2.4.6 Relation to Steps in the Design Process

Several types of uncertainty will be encountered at each step in a performance-based design process or during the process of setting new prescriptive requirements. For example, when developing performance criteria, one will have to deal with scientific uncertainty such as determining what level of carbon monoxide will cause unacceptable consequences and how can one scientifically account for interactions between products of combustion. One will also have to deal with issues of equity and societal values. At present, performance criteria are not established nor agreed upon. Changes to the set of performance criteria selected could cause the same design for the same building to be deemed acceptable in one jurisdiction and deemed unacceptable in another jurisdiction. Uncertainties related to life-cycle use and safety of buildings also arise when selecting performance criteria. Over the life cycle of the building, many factors such as use and occupant characteristics change.

2.5 Need For a Methodology to Treat Uncertainty in the Application of Our Tools

Uncertainty can play an important role in the development and implementation of fire-safety regulations. Beyond being just another step in the process of getting a building approved, properly determining and documenting a level of confidence in the design will have numerous benefits. The treatment of uncertainty is key to ensuring and maintaining an appropriate level of public safety while allowing the flexibility necessary to reduce costs. This is true for all fire-safety engineering calculations, whether conducted to meet a performance-based code, aid in the establishment of a prescriptive requirement, or compare performance options to their prescriptive counterparts. The quantitative treatment of uncertainty will facilitate cooperation among stakeholders by increasing the overall understanding of risks and costs. Distributions of outcomes are a much richer description of what is possible than the typical point-value answers. Though stakeholders and/or policy decisions must still determine how much risk to accept, with thorough uncertainty analyses, these decisions will be informed and free of the uneasiness that typically surrounds acceptance of a deterministic performance calculations.

At present, no method exists for the quantitative treatment of uncertainty in a fire-safety engineering calculations. A method is needed that is both rigorous and comprehendible. Chapter 3 outlines a methodology that provides for the integration of uncertainty analysis into the performance-based design process. The methodology suggested is easily generalized to apply to a broad range of fire-safety engineering calculations. The methodology does not require quantification of all uncertainties in an analysis. However, it provides a means of determining which input parameters have uncertainties that are important to the final decisions. The methodology incorporates ways of handling value judgements and demonstrates how results can be displayed graphically to stimulate discussion among the stakeholders.

2.6 Chapter 2. References

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THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

3. A METHODOLOGY FOR THE TREATMENT OF UNCERTAINTY IN FIRE-SAFETY ENGINEERING DESIGN CALCULATIONS

3. A METHODOLOGY FOR THE TREATMENT OF UNCERTAINTY IN FIRE-SAFETY ENGINEERING DESIGN CALCULATIONS

The fire-safety community needs to begin to move forward from discussing a set of issues and concerns relating to uncertainty in fire-protection engineering to agreeing as a community on practical steps to execute an uncertainty analysis. Chapter 3 presents a generic methodology that quantitatively treats variability and uncertainty and is applicable to a wide range of fire-protection engineering calculations and fire-safety design issues. For example, application of the methodology is appropriate for engineering calculations such as those that predict upper layer temperatures and concentrations of products of combustion. The methodology may also be applied to calculations of time needed to egress. It ties together the issues discussed in Chapter 2 regarding uncertainties in the design process and the problem of switchover and suggests modifications to the current performance-based design process to directly incorporate uncertainty analysis.

3.1 Overview of The Performance-Based Design Process with Uncertainty

The methodology is rigorous but comprehendible. It breaks the process of conducting an engineering design calculation with uncertainty analysis into identifiable steps, each of which can be expanded or contracted to fit specific design problems. Table 3-1 shows the steps in conducting a performance-based fire protection engineering design. The left two columns list the steps in the performance-based design process as detailed in the SFPE guide [*SFPE*, 1999]. The right two columns list the steps in the performance-based process with uncertainty. Steps or parts of steps in bold signify suggested modifications to the current design process. Steps 1-3 are modified by incorporation of treatment of uncertainties noted in parenthesis and detailed in the taxonomy in Chapter 2. The intent of each step does not change; however, the process is made explicit and standardized.

The quantitative methodology for the application of uncertainty analysis is applied throughout Steps 4-8. In step 4 a probabilistic statement of performance is developed. In steps 5-7, candidate designs are developed and a process for evaluating these designs through simulation with uncertainty analysis is described. Step 8 now includes a decision of acceptability that makes use of the results of the quantitative uncertainty analysis. Steps 9 and 10 remain the same. It should be noted that performance-based designs may require an iterative process. If in Step 8 the candidate designs are deemed unacceptable, the process returns to Step 6 to develop new candidate designs. If no acceptable design in found to meet the goals and objectives, Steps 1-3 must be revisited.

Table 3-1. Steps in the Performance-Based Design Process With and Without Uncertainty

PERFORMANCE-BASED DESIGN PROCESS		PERFORMANCE-BASED DESIGN PROCESS WITH UNCERTAINTY	
Step 1	Define Project Scope	Step 1	Define Project Scope **(Uncertainties Related to Life-Cycle Use and Safety of Buildings)**
Step 2	Identify Goals	Step 2	Identify Goals **(Uncertainties Related to Equity and Incorporation of Societal Values)**
Step 3	Define Stakeholder and Design Objectives	Step 3	Define Stakeholder and Design Objectives **(Uncertainties Related to Risk Perception and Values)**
Step 4	Develop Performance Criteria	Step 4	**Develop Probabilistic Statement of Performance (Criteria, Threshold, Probability, Time)**
Step 5	Develop Design Fire Scenarios	Step 5	**Develop a Distribution of Design Fire Scenarios**
		5a	**Select Calculation Procedure(s)**
		5b	**Identify Uncertain Input Parameters**
		5c	**Generate A Distribution of Design Fire Curves**
		5d	**Define Distributions of and Model Correlations Among Other Input Parameters**
		5e	**Select Sampling Method and Determine Number Of Scenarios**
Step 6	Develop Candidate Designs	Step 6	Develop Candidate Designs
Step 7	Evaluate Candidate Designs	Step 7	Evaluate Candidate Designs
		7a	**Calculate A Set Of Values For Each Outcome Criteria and Create Cumulative Distribution Functions**
		7b	**Determine Sensitivity to Elements of Probabilistic Statement of Performance**
		7c	**Evaluate Base Case (Optional)**
		7d	**Determine Effect of Each Candidate Design on Each of The Scenarios**
		7e	**Evaluate Uncertainty Importance**
Step 8	Design Meets Performance Criteria?	Step 8	Design Meets **all Four Elements of Probabilistic Statement of Performance?**
Step 9	Select Final Design	Step 9	Select Final Design
Step 10	Prepare Design Documentation	Step 10	Prepare Design Documentation

3.2 *Steps 1-3.* Define Scope, Goals and Objectives

Many of the types of uncertainties discussed in Chapter 2 are important to consider during the process of setting the scope, goals, and objectives of a project. These three steps are described below; for each step, one example of a type of uncertainty to consider is provided.

The first step in the performance-based design process is to define the scope of the project. The project scope is an identification of the boundaries of the performance-based analysis or design. The SFPE guide suggests consideration of several aspects of scope such as occupant and building characteristics and intended use of the building. In Chapter 2, indeterminacy was discussed as well as uncertainties related to the life-cycle use and safety of buildings. Indeterminacy affects the scope in that it is impossible to know what the occupancy and furnishings will be in a building at some point in the future. Therefore when assumptions are made regarding occupant and building characteristics, some investigation of the sensitivity of the final design to changes in occupant and building characteristics should be made and documented. If switchover occurs for a particular value of one or a combination of analysis parameters, assumptions or values, this needs to be made explicit.

The second step in the design process is identifying and documenting fire-safety goals of various stakeholders. These include levels of protection for people and property and provide for continuity of operations, historical preservation, and environmental protection. For example, when identifying goals of various stakeholders, a mechanism needs to be provided to assure equal outcomes for sub-groups including the building owner, design engineer, architect, code official, and the public (end users). Because it is difficult to assign worth in the usefulness or importance of something and apply it across all individual and societal issues, the key here is that decisions that change if a value, attitude, or risk perception varies must be made explicit in the design documentation.

The third step in the design process is the development of objectives, which are essentially the design goals that have been further refined into values quantifiable in engineering terms. Objectives might include mitigating the consequences of a fire expressed in terms of dollar values, loss of life, or maximum allowable conditions such as the extent of fire spread, temperature, or spread of combustion products. Uncertainties arise here in risk perceptions and values. There is both uncertainty and variability in the way people perceive and value risk.

Capturing differences people have in their perceptions and values related to risk is a necessary step in the design process. For example, it may be a goal of the stakeholders to protect historical features of the building or to protect against business interruption or loss of operating capability. Stakeholders with different values may see these needs differently. It is important to identify where value judgements enter into a performance-based calculation and to make any assumptions explicit regarding values and the impact of different values on the final design.

The following discussion is focused on incorporating uncertainty directly into Steps 4 – 8. Here, we develop a probabilistic design statement, develop a distribution of statistically significant fire scenarios, calculate a set of values for critical outcome criteria, and evaluate each candidate design to determine if the design meets the performance criteria within acceptable uncertainty bounds.

3.3 *Step 4.* Develop Probabilistic Statement of Performance

The fourth step in the design process is the development of probabilistic statement(s) of performance, i.e., and criteria by which to judge the acceptability of the design. These criteria are a further refinement of the design objectives and contain numerical values to which the expected performance of the candidate designs can be compared. Each probabilistic design statement contains a minimum of four elements; probability, time, performance criteria, and threshold value. For example, an objective may be to maintain tenable gas concentrations in the corridor. A corresponding probabilistic design statement for life-safety might specify "The design must allow for a 0.9 probability of having 4 minutes or more before a temperature of 65°C is reached in the corridor." Thus all four elements are included, probability, time, performance criteria, and threshold value. A location is also specified.

There are many issues to be addressed when establishing probabilistic statements of performance. For example, which criterion should one evaluate? One could select instead of or in addition to temperature, levels of carbon monoxide, heat flux, or obscuration. There is disagreement in the literature as to what values of each of these cause negative consequences. The negative consequences must be defined, i.e. should the threshold values represent incapacitation or lethality? Also, the probability element involves determining the level of acceptable risk to the stakeholders and establishing criteria for time to untenability involves understanding behavioral patterns of people in fire as well as making value judgements as to which sub-populations one is trying to protect. The sensitivity of the design to each element of the probabilistic statement of performance is evaluated in *Step 7b*.

Based on this type of sensitivity analysis, a two-tiered probablistic statement of performance may be developed based on any of the four elements as well as location. For example, the probabilistic statement of performance may state, "The design must allow for a 0.9 probability of having 4 minutes or more before untenability based on a temperature of 65°C is reached AND a 0.9 probability of having 6 minutes or more before 100°C is reached. " Other ways to specify the design statement include:

- two probability levels, " Design must have greater than or equal to a 0.95 probability of X AND a less than or equal to a 0.1 or more probability of Y."
- Another variation is "Design must provide for a 0.9 probability of providing 4 minutes before 65^0C is reached and a 0.9 probability of having 8 minutes or more before untenable gas conditions are reached."

These are just a few of the possible specification options. Also, the location of evaluation matters. Untenability can be evaluated as a minimum anywhere in any room, including the room of origin, or it can be evaluated along the egress path. These two analyses may give different results in terms of acceptability.

3.4 *Step 5.* Develop a Distribution of Design Fire Scenarios

One of the most important pieces of the methodology is how to generate a set of realistic input scenarios. It is important that this set include a combination of scenarios that represent statistically both the types of fires and the frequency at which they occur in a given occupancy type. The input scenario generator should integrate information about the uncertainty, variability, and correlational structure of the input parameters. Using an appropriate sampling method (e.g., Monte Carlo Method), a set of any given number of fire scenarios may be constructed. This distribution of scenarios generated will contain the typical cases as well as the worst-case scenarios in the tails of the distribution. The steps involved in developing a distribution of design fire scenarios are: a) selecting a calculation procedure; b) identifying the uncertain and crucial input parameters; c) generating a distribution of design fire curves; d) defining distributions of and modeling correlations among input parameters; and e) selecting a sampling method and determining the number of scenarios.

3.~~4~~ 5 *Step 5a*. Select Calculation Procedure(S)

The next step is to select the calculation procedure(s) to be used in the performance-based design. There are a range of calculation tools and models currently available. The Fire Protection Handbook provides a good overview of the various types of fire models. [*Beyler*, 1991] Fire models are categorized as shown in Figure 3-1. Which model or type of model is selected depends on several factors, including the application of interest. Fire models can be used to predict a hazard, predict a risk, reconstruct a fire, interpolate between or extrapolate beyond test results, or evaluate a parametric variation. The application of fire models for each of these purposes is discussed in [*Nelson*, 1991]. Each of these applications may have purpose at some stage of the performance-based design process.

Fire models are classified into two broad classes: physical models and mathematical models. Physical models are often used to determine laws governing systems. Mathematical models are sets of equations that describe the behavior of a physical system. Thus, physical and mathematical models are interrelated and complimentary. Physical models attempt to reproduce fire phenomena in a simplified physical situation. An example of a physical model is a scale model which may be used in place of an expensive full-scale experiment. The most widespread physical scaling laws in fire are known as "Froude modeling," which is applicable to buoyant flows associated with fires. Froude modeling requires that the ratio of buoyant forces to inertia a forces be maintained. Froude modeling has been used successfully to understand plume flows, ceiling jet flows and flame heights. However, because different fir phenomena scale differently, it is not generally possible to study complex fire situations in small scale. For example, it is not possible to scale convective flows and radiation at the same time thus Froude modeling cannot be applied readily to fire problems where radiation is important. Physical modeling does not always involve major reductions in physical scale. Physical models may seek to simplify complex phenomena into a manageable and understandable problem. All standard fire tests are physical models of fire behavior.

Mathematical models are classified into special purpose and enclosure fire models. Special-purpose fire models are designed for single-phenomena analysis such as flame spread rate, flame height, time to flashover, time to response of a smoke detector, or time needed for egress. Special purpose models for calculation of each of these phenomena and many others are described in [*Walton and Budnick*, 1991]. Enclosure fire models are used to predict the development over time of build-up of heat and products of combustion in a single room or in a multi-room building.

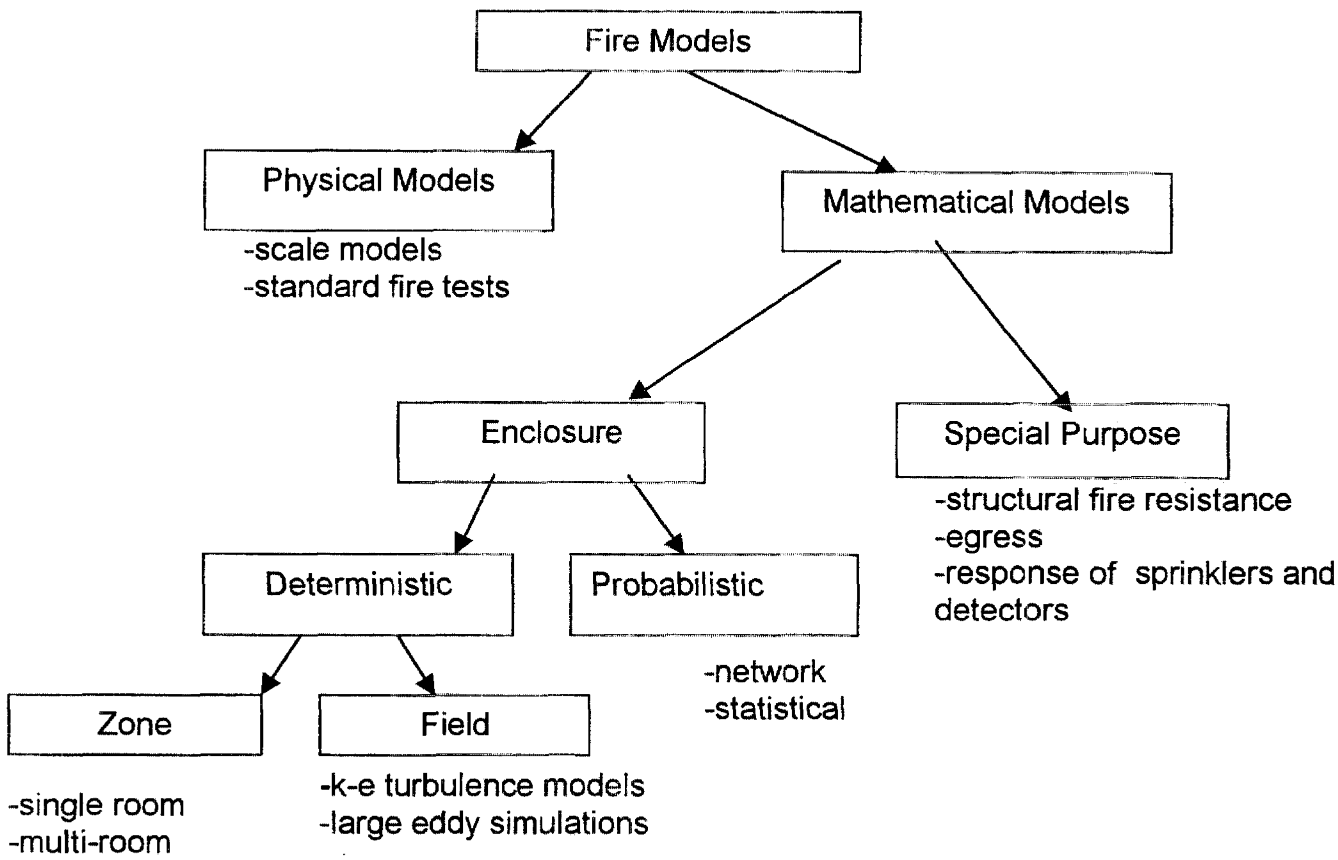

Figure 3-1. Classification of Types of Fire Models

Mathematical models are further classified into probabilistic and deterministic models. Two types of probabilistic models are network and statistical. Network models are fire growth models in which the transition from one fire stage to another and the effectiveness of fire suppression systems, passive fire protection and so on is governed by user-assigned probabilities. Statistical models represent the probability of occurrence as it is determined from historical data. Probabilistic fire models are described in more detail in the *Fire Protection Handbook*. [*Watts*, 1991]

Deterministic models range from one-line correlations of data to highly complex models requiring days of computing time. The unifying aspect of these deterministic fire models is that the course of a fire is fixed by the variables that establish the environment in which it occurs. The physical conditions that determine progress and outcome of the fire are called the fire scenario. Thus, for all deterministic fire models the formulation of the fire scenario is of critical importance.

Deterministic fire models may be zone models or field models. The most commonly used type of deterministic enclose fire model is the zone model. The zone model concept divides the burning enclosure into several distinct zones with uniform fire characteristics. Ordinary differential equations expressing conservation of mass and energy are applied to each zone and solved numerically in combination with empirically derived correlations for phenomena not modeled from first principles, for example, entrainment. Typically, zone models provide results in one dimension (e.g. upper layer thickness and temperature, lower layer thickness and temperature). Early versions of zone models calculated conditions in a single room only. Multi-room models capable of calculating the build-up and spread of heat and products of combustion throughout several rooms and several floors of a building are now available. An overview of the leading zone fire models is given in [*Walton*, 1995; *Walton and Budnick*, 1991].

Field models represent the second class of deterministic models. Field models solve the fundamental equations of mass, momentum, and energy at each element in a compartment space that has been divided into a grid of small cubes. This calculation accounts for physical changes generated within the cube and changes in the cube originating from surrounding cubes. This model permits the user to determine the conditions at any point in the compartment. Field models require significantly more computational time than do zone fire models but are needed when key assumptions underlying zone fire models (e.g. uniform properties of the upper and lower layers) do not hold. Examples are spaces with large volumes and/or high ceiling heights. An overview of computational fluid dynamics theory and a summary of selected field models are given in the SFPE Handbook. [*Stroup*, 1995]

Field models are distinguished by the way they handle turbulence. The flows occurring in room fires are turbulent, generating eddies or vortices of many sizes. The energy contained in large vortices cascades down into smaller and smaller vortices until the viscous forces dominate over the inertial forces and the energy is diffused into heat. The scale at which this happens is much smaller than a millimeter. Since spaces of interest to fire modelers are orders of magnitude larger, practical computational times limit the grid size to values much greater than the smallest of practical turbulence; thus, models are needed to account for the effect of small-scale fluid motion in the larger-scale control volumes.

One widely used turbulence model called the k-epsilon model, utilizes two additional differential equations per control volume: k governs the distribution of turbulent kinetic energy and epsilon governs the dissipation of the local energy. These k-epsilon models use several empirical constants and less accurately model behavior at the wall. A second approach to handling turbulence is the large eddy simulation model, which has been used to carry out 3-dimensional time-dependent simulations of fire. Smoke is simulated by tracking a large number of Lagrangian elements originating in the fire. The grid size still exceeds the minimum that would be required to model turbulence fully, so viscosity is simulated as higher than it is by using a lower Reynolds number [*Baum et al.*, 1997]. The use of computer models to predict temperature and smoke movement in high bay spaces has been studied using both enclosure zone fire models and k-eplison field models. [*Notarianni and Davis*, 1993]. Comparisons of fire model predications using several zone and field models were compared with fire experiments conducted in an aircraft hangar [*Davis et al.*, 1996].

To conduct a performance-based design with uncertainty as detailed in Table 3-1 and described in this chapter, many of the types of models described here may play a role. For example, a deterministic fire model may be selected to estimate the build-up of heat and products of combustion throughout the building. The performance-based design process with uncertainty treats the inputs to this deterministic model as random variables; thus both statistical and physical models are needed to develop representations of and correlations among the input parameters. To judge acceptability of a design, additional special purpose models may be used to calculate the time to activation of a sprinkler or detector, the time needed to safely egress a building, or the time to structural failure.

The methodology for the quantitative treatment of uncertainty may be applied to any of the types of fire models. The methodology addresses uncertainties in the application of these tools; however, each of the calculation procedures or models have inherent scientific uncertainties which arise when physical processes are not modeled due to lack of knowledge of how to include them. When processes are modeled based on empirically derived correlations, and/or when simplifying assumptions are made for operational practicality of a model or calculation. Scientific uncertainty inherent in the tools themselves are not addressed by the methodology presented here.

Deterministic enclosure fire models share many of the same limitations. One such limitation shared by fire calculation procedures is the absence of a fire growth model. These models all require the user to specify the fire in terms of the rate of energy and mass released by the burning item as a function of time. Such data are obtained by measurements taken in large- and small-scale calorimeters, or from room burns. Potential sources of uncertainty include the following: measurement errors related to the instrumentation; the degree to which radiation feedback affects burning rates and combustion chemistry; uncertainties due to scaling factors used to extrapolate small-scale data to a full-size item; and uncertainties related to the representativeness of the item burned to the actual item ignited during an actual fire (e.g. a couch or chair burned in a calorimeter will not necessarily represent adequately the chair or couch in the building being designed.

Other shared scientific uncertainties, particularly among zone fire models, result from the following:

- All zone fire models divide each room into a small number of control volumes, each of which is assumed internally uniform in temperature and composition.
- Empirical correlations are used for flow and entrainment coefficients.
- There is a lack of knowledge regarding post-flashover chemistry.
- User-specified hydrocarbon ratios and species yields are used by these models to predict concentrations in each room.
- Entrainment coefficients are empirically determined values, and while small errors in these values will have a small affect on the fire plume or the flow in the plume of gases exiting the door of that room; in multi-room compartment models errors are multiplicative as the flow proceeds

through many compartments, possibly resulting in a significant error in the furthest rooms.

- No generally applied design or analysis procedures exist for the interaction of the automatic sprinkler and the plume.

Uncertainties arise when physical processes are modeled based on empirically derived correlations and/or simplifying assumptions are made. These factors lead to uncertainties in the results. For most fire models and calculation procedures, very different answers can result depending on the calculation limitations and level of detail of the modeling. Computational limitations lead to simplifications and approximations that induce uncertainty. Also, models are often used outside of their intended applications due to poor documentation or misunderstandings. Several researchers [*Lantz*, 2000; *Siu et al.*, 1999] suggest methodologies to aid in the identification of a model or set of models upon which predictions may be based and to aid in quantifying the uncertainties inherent in the use of these models. However, the method for the treatment of uncertainty presented in this thesis does not address scientific uncertainties in the calculation methodology itself.

3.6 *Step 5b.* Identify Uncertain and Crucial Input Parameters

Once a calculation procedure is chosen and candidate designs have been selected, the input parameters necessary for the calculation are evaluated. It must be determined which of the input parameters will be treated as uncertain. Ideally, only parameters or combinations of parameters with uncertainty great enough to change decisions regarding the final design are treated as uncertain. These are referred to as the crucial variables. Unfortunately, we do not always know *a priori* which of the input parameters possess crucial uncertainty. Therefore, we must use a combination of judgement and results of previous analyses. The uncertainty importance of each of the uncertain input parametersis determined so that future analyses may be simplified. Eventually, only a few key parameters may be needed to capture the uncertainty in each calculation.

3.7 *Step 5c.* Generate a Distribution of Design Fires

Design fire scenarios are made up of both possible fire events (heat release rates curves) and characteristics of the material burning, of the building, and other relevant information such as weather conditions. A set of design fires is established to mimic the type and frequency of fires expected for that occupancy. These design-fire curves are based on statistically collected data, judgement and the goals of the design. Each design fire is assigned a likelihood of occurrence.

3.8 *Step 5d.* Define Distributions of and Correlations Among Other Input Parameters

The uncertainty and variability surrounding each variable must be captured in the mathematical description of that variable. Any and all available knowledge regarding the value of that parameter should be incorporated in the input scenario generator. This includes empirically measured values, known variations, and statistically compiled data. For example, for a given occupancy type, the NFPA publishes statistical data on the percentage of fires that start in each potential room of fire origin. This information should be incorporated into the random scenario generator so that the generator mimics these statistics. Distributions can be constructed for variables such as temperature, wind, and relative humidity from regional data published by the national weather service data. Methods for quantifying measurement uncertainty [*American National Standards Institute*, 1997] are used to capture uncertainty and variability in empirically measured parameters such as rates of production of products of combustion. In many cases, where hard data do not exist and are not possible to create, expert elicitation is needed to quantify the uncertainty.

When two or more variables are correlated, knowledge of the value of one variable tells one something about the value of the other variable(s). Correlation among variables is modeled so that the input scenario generator will not generate unrealistic scenarios. For example, if the design incorporated a weather module, a month of the year would be randomly selected. For that given month, a value is sampled from an outdoor temperature distribution based on

National Weather Service data for that region. Outdoor temperature is correlated to external pressure, wind, relative humidity, likelihood of windows/doors being open, indoor temperature and pressure, and initial fuel temperature. This prevents the software from generating, for example, a scenario where there is a fire on a below freezing day in August in California, and all the windows are open.

3.9 Step 5e. Select Sampling Method and Determine Number of Scenarios

A sampling method, such as Monte Carlo, Latin Hypercube, or quasi-random must be selected. By sampling a single value from each of the distributions in the input scenario generator and combining those numbers with the values of input parameters that are being treated as certain, any number of independent fire scenarios may be generated.

A large number of scenarios increases the statistical significance of the results. However, this relationship is dependent on the sampling method chosen and is not linear. Using 2,000 runs may not provide any more insight than using 500. The number of scenarios chosen depends upon: 1) the number of uncertain input parameters, 2) the average calculation time per scenario for the calculation procedure chosen, and 3) the statistical significance needed. When conducting correlational analyses between inputs and outputs, one obtains importance or correlation coefficients, c, between 0 and 1. Hald provides a formula for determining the relationship between the number of runs, n, and the statistical significance (as measured by a t-test) of the correlation coefficient. [*Hald*, 1952]

$$t = \frac{c}{\sqrt{1-c^2}}(\sqrt{n-2}) \qquad (3\text{-}1)$$

The value for t is related to the confidence level which is typically chosen as 95%.

3.10 *Step 6.* Develop Candidate Designs

The candidate design is intended to meet the project requirements. A candidate design includes proposed fire-protection systems, construction features, and operations that are provided in order to meet the performance criteria when evaluated using the design-fire scenarios.

3.11 *Step 7.* Evaluating Candidate Designs - Introduction

Each candidate design must be evaluated using each design-fire scenario. The evaluations indicate whether the candidate design will meet the elements of the probabilistic statements of performance. Only candidate designs that meet the performance criteria may be considered as final design proposals. Without the quantitative treatment of uncertainties in the design, each calculation will provide a point estimate only of the important outcome criteria. For example the performance criteria for a design may be a 100°C maximum temperature reached in the upper layer. The time to an upper layer temperature of 100°C may be predicted as 175 seconds, and the time to activation of a sprinkler may be predicted as 171.2 seconds by a given computer model. Because the sprinkler is predicted to activate before the performance criteria is exceeded, this would be deemed an acceptable design. However, the uncertainty in the prediction of time to 100°C may be +/- 20 seconds. This would mean that the temperature in the room may reach 100°C at 155 seconds or before activation of the sprinkler. Also, the predicted time to activation of the sprinkler has an uncertainty surrounding it as does the temperature at which untenability might actually occur.

The performance-based design process with uncertainty will aid in the calculation of a range of possible values for each key outcome criterion instead of a single point value. This methodology is useful for and may need to be applied to several parts of the design calculations. For example, it could be applied to the calculation of upper layer temperatures, to the prediction of time to response of devices, and to the prediction of time needed to egress a building.

3.12 *Step 7a.* Calculate a Set of Values for Each Outcome Criterion

A single value will be determined for each outcome criterion calculated for each design-fire scenario run. Much information can be obtained from observation of both the range of values for criteria of interest and from cumulative distribution functions generated from the set of all values.

If criteria are time series values, each scenario will predict a different curve of the key outcome criteria vs. time. For example, if upper layer temperature is the criterion of interest, four design fire scenarios would produce four curves of upper layer vs. time. Figure 3-2 shows a representative graph of the value of outcome criterion A plotted against time from ignition (in seconds). For any give design, there would be as many curves as there are design fire scenarios calculated. One can see that the curves vary in both the magnitude of the peak value and in the time to the peak value.

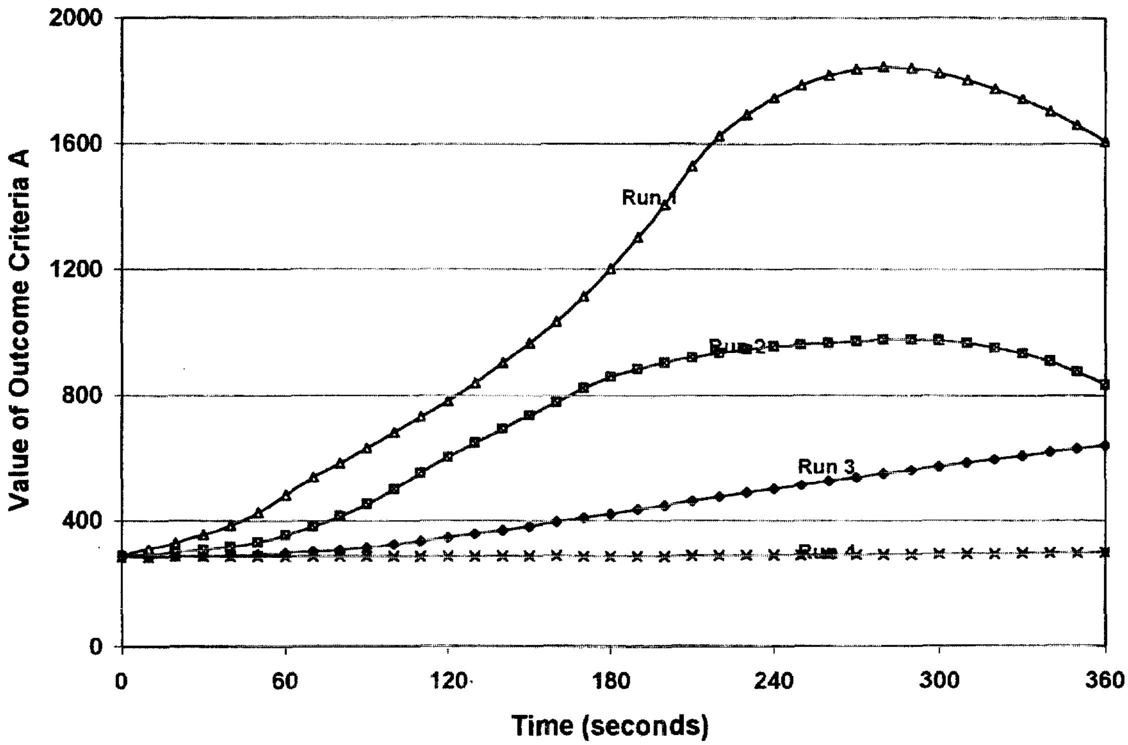

Figure 3-2. Variation in Prediction of Time Series Values of Outcome Criterion A

The range of values predicted from the set of design-fire scenarios represents the uncertainty in the value of the outcome criterion. From the set of predicted values of a single outcome criterion, a cumulative distribution function may be generated. This is done by graphing the value of the criterion against its rank order. For example, for *n* design-fire scenarios, *n* values of a given criterion are generated. These values are then sorted in descending order. The largest value is graphed vs. $1/n$ the second largest against $2/n$ .... and the smallest value against n/n or one.

An example of a cumulative distribution function (CDF) is shown in Figure 3-3. The time to reach a threshold value of one or more of the tenability criteria, that is, a value determined to cause injury or death, can be determined from the time series predictions. The threshold value may be a particular temperature or carbon monoxide level or a parameter used to represent some synergistic effect of a combination of the tenability variables. One value of time to untenability is obtained for each scenario run. The set of all possible values provides a distribution of the outcome criteria.

Figure 3-3 shows that for the distribution of design fire scenarios, there is almost a 1.0 probability that the time to a critical value of criterion A is 30 seconds or more. Likewise, there is a 0.75 probability that the time to this value is 120 seconds or more, a 0.50 probability that it is 180 seconds or more, and a 0.1 probability that it is 390 seconds or more.

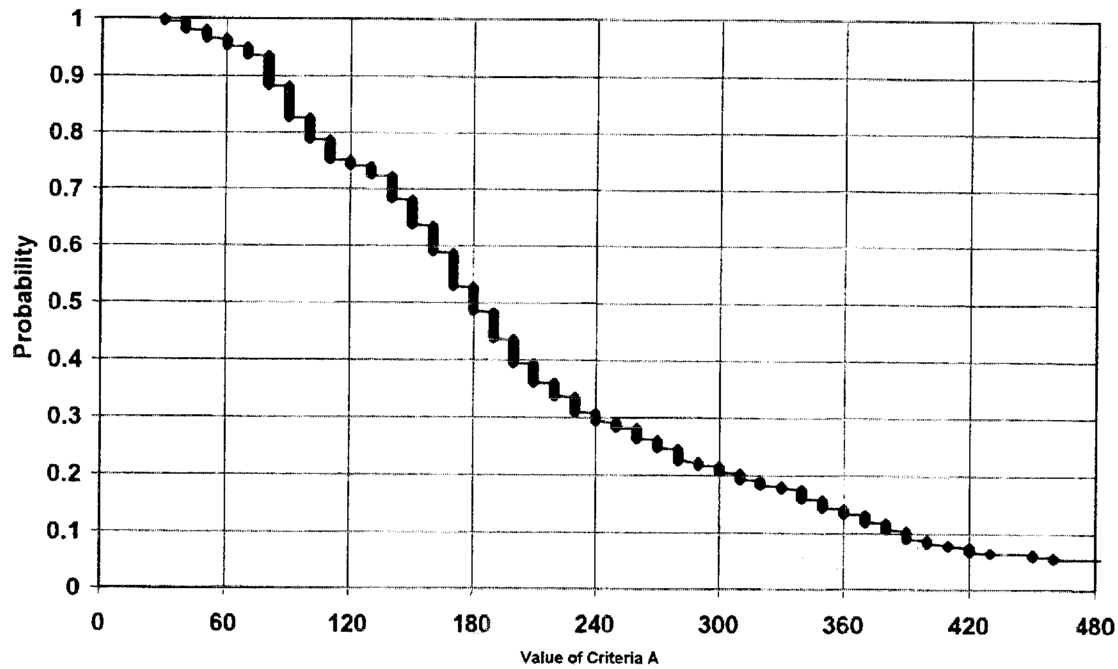

Figure 3-3. Cumulative Distribution Function of Time to Critical Value of Criterion A

3.13 *Step 7b.* Determine Sensitivity of Outcome Criteria to Elements of Probabilistic Statement of Performance

The sensitivity of key outcome criteria to each of the four elements of the probabilistic statement of performance upon which a design is judged must be known before should policy and good design practice can be established. Elements such as criteria, threshold values, probabilities, and times are not mandated nor agreed upon by fire safety and health professionals nor the public. Therefore, major conclusions of all designs should be checked in order to demonstrate the sensitivity to uncertainty in each of these elements. This might include checking for times to untenable temperature, carbon monoxide, carbon dioxide, and reduction in oxygen. It may include checking for synergistic effects of the presence of these substances. It may also be appropriate to evaluate for heat flux and visibility.

The same design may be judged on two different performance criteria or by two different critical values of the same performance criterion. Figure 3-4 shows an example of time to untenability based on different values of upper layer temperature. This type of presentation could also be used to determine what the affect on time to untenability is by selecting a group of tenability criteria or by including different sets of components in the specification of tenability criteria.

This type of evaluation is a good way to focus discussions among stakeholders as to what the tenability criteria need to be, what the effect the selection of different threshold values of tenability criteria are, what probability level is acceptable to the stakeholders, and how to select the final design. At the end of this step, final performance criteria must be selected for use in judging acceptability of designs and choosing a final design.

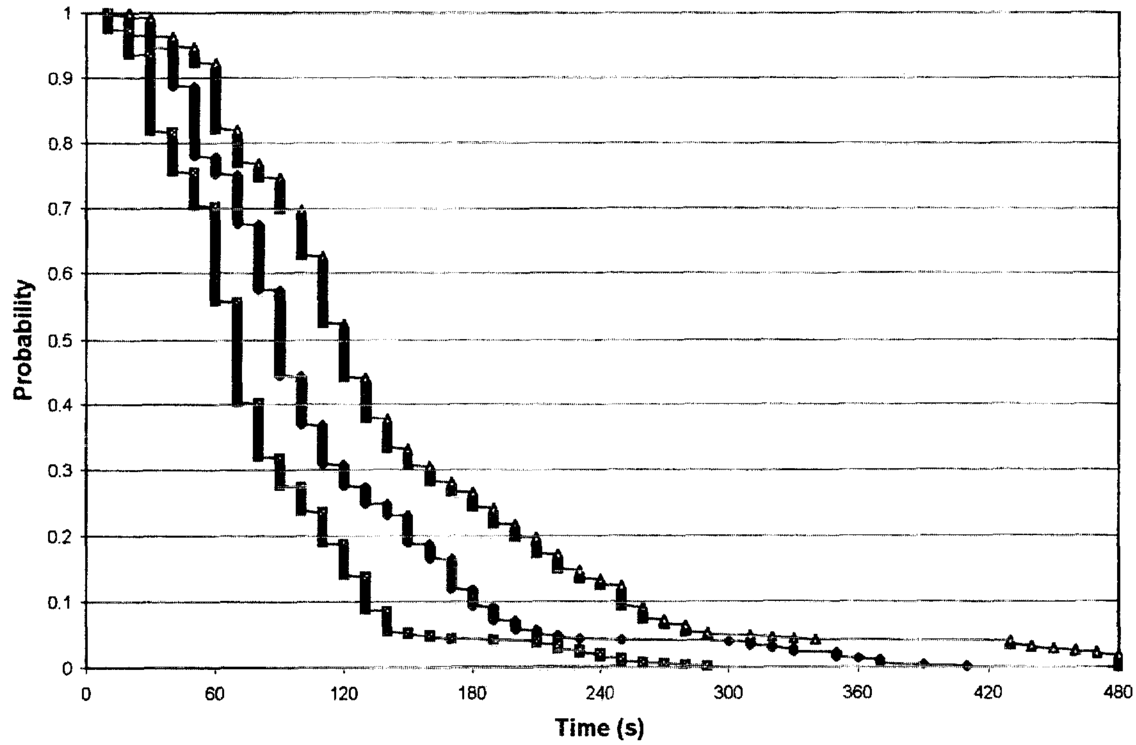

Figure 3-4 **Probability Of Having X Seconds Or More Before Untenable Upper Layer Temperatures Are Reached For Three Different Values Of Untenable Temperature**

3.14 Step 7c. Evaluate Base Case

Depending upon the needs and the scope of the project, it is helpful to compare a candidate design to a base-case design. The base case can be the design that meets the prescriptive-code, the design that includes the fire-protection options currently in the building, or the design with no active fire suppression systems. The purpose of having a base case is to benchmark the effects of fire on the building and the building conditions against each of the designs.

In Figure 3-5, the results of multiple scenario runs are used to show the probability of safe egress graphed against the time to untenable conditions for two different designs. Design 1 and Design 2 may represent two different performance designs or a performance design and a prescriptive design. Reiss discusses the need for this comparative approach [*Reiss*, 1998]. The graph shows two design curves that exhibit crossover. Design 1 provides a higher probability of tenability out to 50 seconds; however, Design 2 provides a higher probability of tenability at longer times.

Another way that the acceptability of a design is judged is by comparison of the level of safety provided to the level of safety provided by the corresponding prescriptive design. There is uncertainty associated with the prescriptive design also. The prescriptive code will mandate certain building materials and fire-detection and suppression schemes. However, uncertainty and variability remain in the weather, ventilation conditions, human behavioral aspects, and where and how the fire will start. Thus, multiple scenarios can be constructed in a parallel manner to that shown above, holding as constants those factors required by the prescriptive code. Thus, a CDF for the prescriptive code can be generated and compared to the CDF for the performance code.

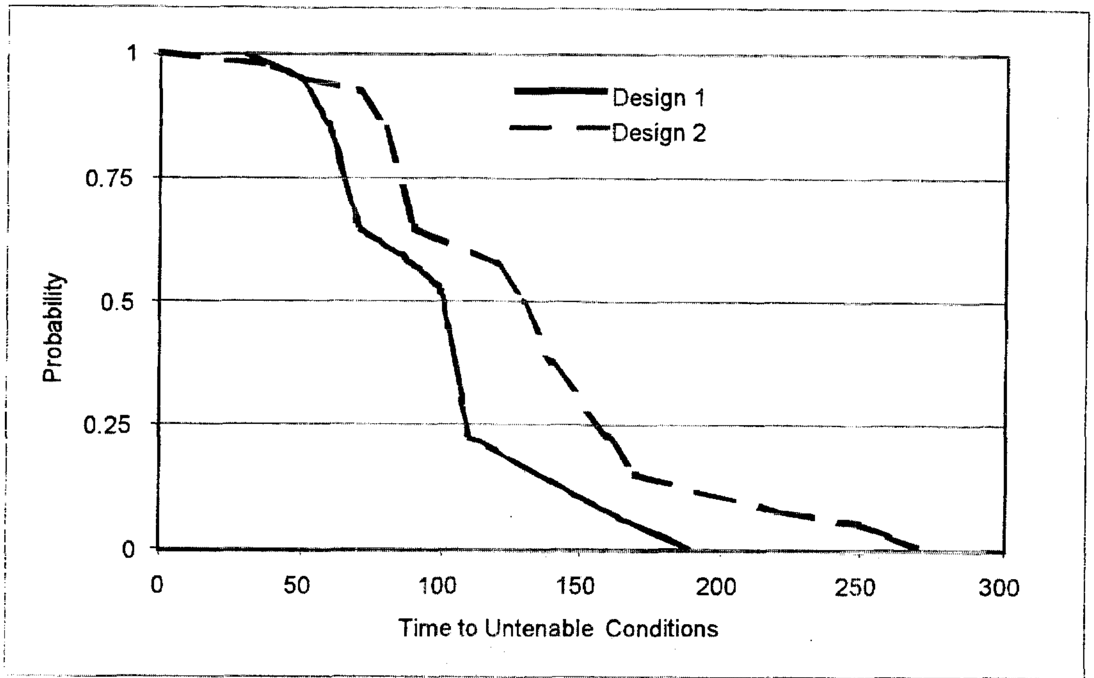

Figure 3-5. Comparison of Cumulative Distribution Functions of Time to Untenable Conditions for Two Different Designs

3.15 *Step 7d.* Determine The Effect Of Each Candidate Design On Each Of The Scenarios

To compare two different candidate designs, we may want to look at the distribution of differences between the two designs based on the final selected performance criteria. One may consider differences between a design and the reference base case or differences in time to untenability provided by Design 1 vs. Design 2. For example, Figure 3-6 is a cumulative distribution function of the difference in time to untenability provided by Design 1 minus the time to untenability provided by Design 2.

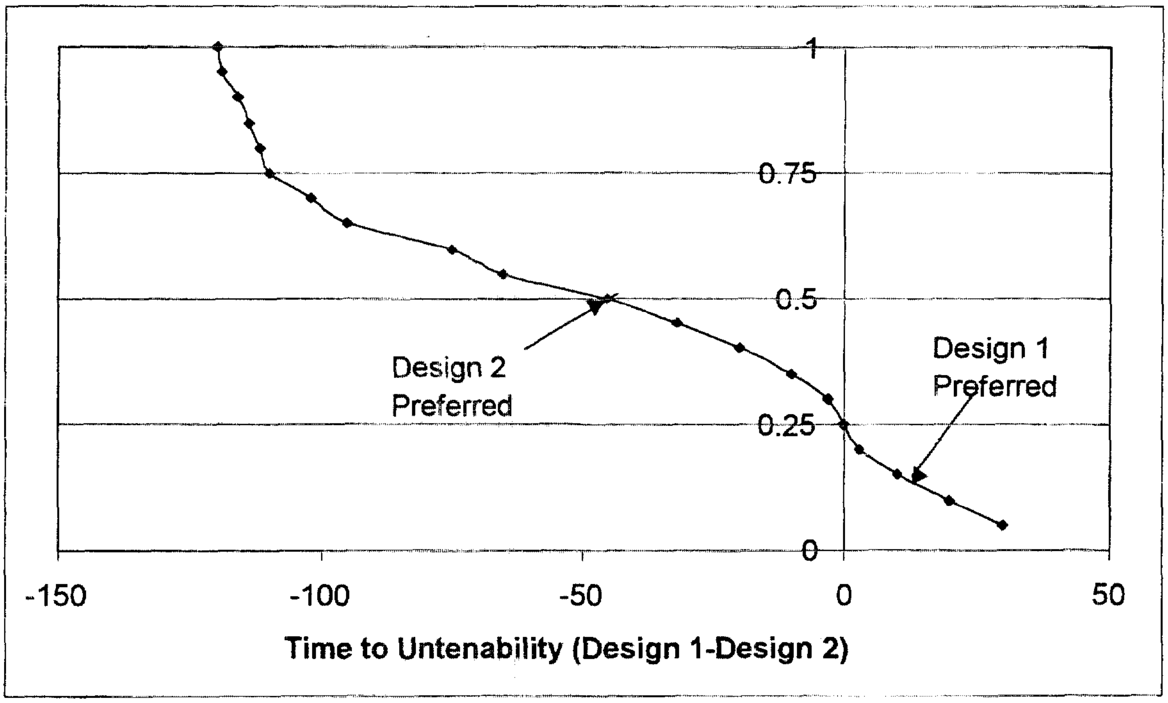

Figure 3-6. Cumulative Distribution Function of Time to Untenability Design 1 Minus Design 2

Figure 3-6 shows that there is a 0.25 probability that Design 1 will provide a longer time to untenable conditions than Design 2. Conversely, there is a 0.75 probability that Design 2 will provide a longer time to untenability than Design 1 and a 0.25 probability that the difference will be 100 or more seconds better. In selecting a final design, it may be helpful to investigate what factors might lead to Design 1 providing more time to untenability vs. Design two, which could point out ways to improve the design.

3.16 *Step 7e*. Evaluate Uncertainty Importance

An importance analysis is a particular type of sensitivity analysis that determines which of the uncertain input variables contributes most to the uncertainty in the outcome variable. The results are used simplify future performance-based designs by identifying the one or two, or small group of most important inputs. Importance here is measured by the correlation between the output value and each uncertain input. Each variable's importance is calculated on a scale from 0 to 1 (or –1). A correlation of 0 indicates that uncertainty in the input variable has no affect on the uncertainty in the output parameter.

The input parameters can be correlated to composite or derived outcomes, (i.e., an outcome that is not directly an output of the model but one that is derived from the output data). Likewise, input variables can be combined (for example, the volume of a room can be determined from the dimension). Room volume may be correlated with key outcome criteria, for example, peak temperature or time to peak temperature.

Importance analysis can be used to simplify a future uncertainty analysis by determining the input uncertainties that are most crucial. This can simplify the process for a class of buildings and can demonstrate where additional research would be effective in reducing uncertainty and insuring a safer, more predictable building. It must be remembered, however, that correlation does not equal causation. Thus, any apparent strong correlation that is counter intuitive should be investigated with should engineering judgement. Also, for each design, the value of the correlation coefficient that is statistically significant will depend on the number of scenarios run and the sampling method used.

3.17 *Step 8.* Judging A Design's Acceptability Based on All Four Elements of Probabilistic Statement of Performance

There are two ways to judge acceptability of a design. The first is based on the minimum time to untenability anywhere in the building, including the room of origin. The second is the time to untenability along the egress path. In general, for both cases, cumulative distribution functions are used to judge acceptability of a design. For example, Figure 3-3 is a cumulative distribution function of the time to a specific value of criterion A in the room of origin. If the probabilistic statement of performance required a 0.9 probability of having 30 seconds or more before reaching this value, it can be determined from the CDF that this criterion is met. In fact, Figure 3-3 shows that there is a 0.9 probability of having 80 seconds or more. However, if the probabilistic statement of performance requires a 1.0 probability of having 50 seconds or more, Figure 3-3 shows that this criteria is not met because the CDF demonstrates a 1.0 probability of having only 30 seconds or more.

Another way of judging the acceptability of a performance-based design is with a time-to-egress analysis. The time needed to egress a building is often represented in the literature as the time to detect the fire, plus the time to react, plus the time to travel to a safe place. This is represented mathematically below:

$$\text{time}_{\text{egress}} < \text{time}_{\text{untenability}} \tag{3.2}$$

$$\text{time}_{\text{egress}} = \text{time}_{\text{detect}} + \text{time}_{\text{react}} + \text{time}_{\text{travel}} \tag{3.3}$$

One problem with this approach is that it is very difficult to predict human behavior in terms of reaction time and travel time in a fire event. There is both variability due to age and health of the individual and uncertainty as to individual goals and concerns (e.g., will the person try to fight the fire, locate valuables, rescue pets, or notify other occupants about the fire). The methodology described in this chapter may be applied to egress calculations; however, since these are difficult to predict, it is suggested that perhaps these are best handled as societal and policy decisions. Regulatory decisions may be made as to the available safe egress time. For example, more time may be mandated for a health-care facility, where patients may be non-ambulatory and/or asleep at the time of the fire, than in an office building where occupants are generally awake and healthy.

3.18 Steps 9-10 Select Final Design and Prepare Documentation

Candidate designs that satisfy the probabilistic design statement(s) may be considered for selection as the final design. When more than one candidate design meets all four elements of the probabilistic statement of performance, other factors such as cost and preference are considered. When considering multiple designs or designs with very different features, a multi-criteria decision analysis model may be developed to aid in selecting the final design.

Proper documentation of a performance design is critical and should be written so that all parties involved understand what is necessary for the design implementation, maintenance, and continuity of the fire protection design. The SFPE Guide to Performance-Based design suggests that the documentation have four parts: the fire-protection engineering design brief, the performance design report, the detailed specifications and drawings, and the building operations and maintenance manual. It is important that the performance-based design report convey the expected hazards, risks, and expected performance over the entire building life. It should include the project scope, goal, and objectives, the probabilistic design statements, a discussion of the design fires and design fire scenarios, and any critical design assumptions.

3-19 Chapter 3. References

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THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

4. APPLICATION OF METHODOLOGY TO A CASE STUDY

In order to demonstrate application of the performance-based design process with uncertainty and as to answer several research questions, the methodology is applied to a case study of an actual building. Although described in sequential order, development of the methodology and its application to the case study occurred concurrently. An iterative learning process helped refine the methodology into a process that is both usable and modular. Many lessons were learned in the application of the case study. These are described as an aid in conducting future studies.

Because of the dual purposes of this case study, no conclusions are or should be drawn about fire-protection options for this particular building. In several instances, representations of input parameters were selected to answer a specific research question and varied from, or were different than, the actual parameters of the case study. Through calculation of the case study, however, many techniques are demonstrated, and generalized insights can be drawn that should be useful to a wide variety of stakeholders. Chapter 4 guides the reader from the establishment of goals and objectives through the generation and calculation of a set of design fire scenarios for the case study (steps 1-5e of Figure 3-1). Chapter 5 will present the analysis of the results of the calculations and the process of selecting a final design (steps 6 - 10).

4.1 Selection of A Case Study

The case study presented here is based on a larger performance-based design that was first presented in 1998 at the 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods [*Sullivan*, 1998].
The building is an existing residential high-rise building built in the early 1960's. Massachusetts General Law requires that the building be retrofitted throughout with automatic sprinklers. Performance-based design solutions are allowed and were investigated as an alternative to providing full sprinkler coverage throughout the building. The potential for such an engineering analysis has recently been realized in the United States through the "equivalent level of fire safety" concept by the Federal Fire Safety Act of 1992 and defined by the United States General Services Administration in 1994.

The building is a sixteen-story reinforced concrete and masonry building with a basement. The building represent Type 1B noncombustible construction. Each story is approximately 1,400 m^2 and 2.7 m high. The typical floor layout consists of a common corridor in the center of the building with dwelling units on each side and stairwells at both ends. There are two-hour fire resistant rated-walls between the dwelling units and two-hour fire resistant rated floor/ceiling assemblies throughout the building. The building consists of studio, one-bedroom and two-bedroom units.

4.2 Steps 1-3. Scope, Goals and Objectives

The scope of this analysis is limited to a one-bedroom unit in the building. Figure 4-1 provides a schematic of the apartment layout modeled including room dimensions and vent numbers. The design intent is to determine the time available for safe egress with no sprinklers as well as installation of automatic fire sprinklers in various locations. Note that the scope of this study, conducted to demonstrate application of uncertainty analysis, is smaller than the scope of the original case study that was tasked to make decisions regarding multiple fire protection options for the entire building.

The original design had six performance goals that qualitatively addressed life-safety intentions and were agreed upon by the stakeholders. The full set is listed here for interest. The current case study addresses goals 1-4.

1) Limit the probability of fatalities or major injuries to those occupants intimate with the fire ignition.

2) Limit the probability of minor injuries to those occupants in the dwelling unit of fire origin.

3) Limit the probability of reaching hazardous levels of smoke and toxic gases to the dwelling unit of fire origin before safe egress can be achieved. At no point in time should the smoke conditions in any compartment endanger persons in those compartments or prevent egress through those compartments.

4) Limit the probability that occupants outside the unit of fire origin will be exposed to the products of combustion in a manner that causes injury.

5) Limit the flame damage to within the dwelling unit of fire origin (this includes taking into account the possibility of exposure up the exterior of the building).

6) Limit the incident to one manageable by the fire department without major commitment of resources or excessive danger to firefighters during all phases of fire department operation.

4.3 *Step 4.* Selection of Performance Criteria and Range of Values

The next step in the process requires the selection of performance criteria that will satisfy the design objectives and will be used to evaluate the candidate designs. A complete statement of the design criteria must include several elements: the performance criterion (or set of criteria), threshold value(s), and the required probability of having a specified length of time to reach threshold levels. For example, because this is a life-safety design, one complete specification of the design criteria might be, "design for a 90% probability of having two minutes or more before untenability based on a criterion of 65°C reached anywhere on the egress path."

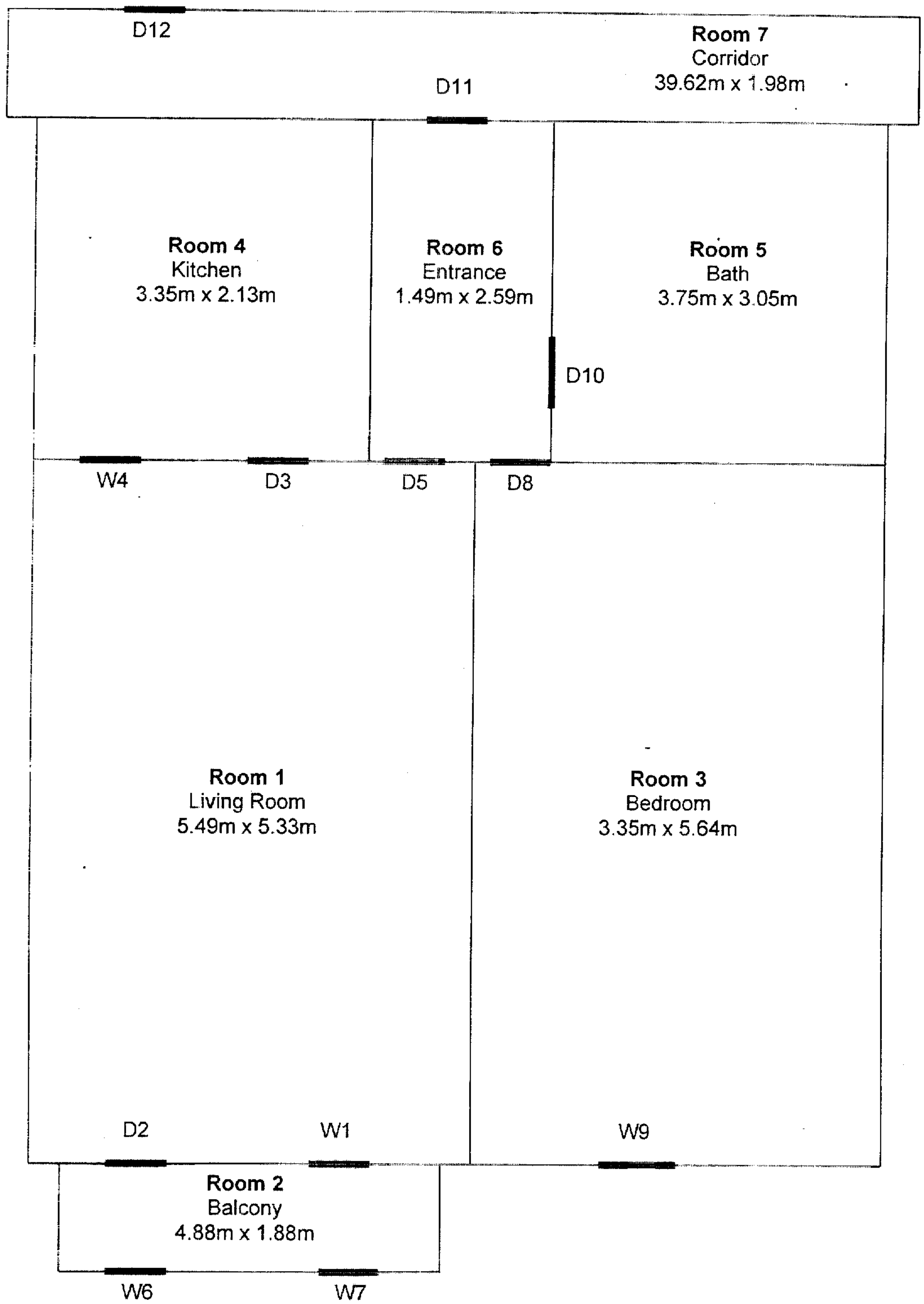

Figure 4-1. One Bedroom Apartment Layout (not to scale)

Eventually, these design criteria could be standardized by a regulatory authority for a given class of buildings and occupant characteristics. For example, designs may be required to provide longer times to untenability and/or be based on more stringent tenability criteria for nursing homes, where occupants are elderly and/or sick, and also may be asleep or medicated, versus an office building. However, before design criteria can be appropriately set by either a regulatory body for a class of buildings or by a group of stakeholders for a specific building, studies are needed on the difference in predicted times to untenability based on selecting different measures of tenability and on the uncertainties surrounding the critical threshold levels of these measures. This case study provides one such data set that compares time to untenability based on various performance criteria discussed in the literature and of interest in a residential setting. It is a fairly comprehensive but not exhaustive look at occupant effects.

4.3.1 Potential Effects on Occupants

There are a number of potential effects on occupants during a fire. These include impaired vision from the smoke, pain to the exposed skin and the upper respiratory tract followed by burns, hyperthermia due to the effects of heat preventing escape and leading to collapse, and asphyxiation due to inhalation of toxic gases. All of these effects can lead to permanent injury and, except for impaired vision from smoke, can be fatal if the degree of exposure is sufficient. For a hazard assessment, the major considerations are 1) the time when affects are likely to occur that might influence occupant behavior and delay escape, 2) the time when incapacitating effects are likely to occur that might prevent escape, and 3) the likelihood that exposure will result in permanent injury or death. Thus, loss of tenability can occur from smoke, irritants, asphyxiates, or heat. These effects lie on a continuum from little or no effect at low levels to relatively severe incapacitation or death at high levels. [*Purser*, 1995]

4.3.2 Uncertainties Related to Critical Exposure Levels

Purser explains that the methods for assessing the effects of toxic gases are based partly on reported effects in humans and partly upon experimental data from animal studies. These methods involve either the exposure dose or concentration predicted to produce a given effect on humans exposed to fire effluent. However, different individuals will exhibit a variable response based on many factors, the most important of which are age and health of the cardiovascular and pulmonary systems. Individual exposure doses or concentrations for the response would in practice be statistically distributed around the mode in a probability curve.

Also, many of the values given in the literature for animal populations are LC_{50}s. An LC_{50} represents the concentration causing 50% of the animals to die for a given exposure time. In fire-protection engineering, we want to design for an LC_0, or the concentration below, which no lethal effects are observed. Many of the LC_{50} values reported in the literature were assessed over a 30-minute time frame. In fire-protection engineering practice, however, it is also important to predict what will happen to a subject exposed to a higher concentration for a shorter period of time.

Although there are uncertainties related to critical exposure levels, it is necessary to make some estimate of the point where conditions become so severe in terms of these hazards that effective escape attempts are likely to cease, and where occupants are likely to suffer severe incapacitation, injuries, or death. In a design context for buildings, the important consideration is to set reasonable tenability limits for occupants to use a particular escape route or remain in a place of safety. It must be determined what the likely effects of any exposure are on the capability of occupants to escape. Because of uncertainty in the applicability of animal data to humans, variations among response of human sub-populations, designing for no lethal effects, and the potential difference in time frames, scientists and engineers have suggested a wide range of values suitable as design tenability criteria.

4.3.3 Concentration Multiplied Times "Time Effects vs. Thresholds"

Limits of safe exposure can be defined based on the moment at which a critical threshold value is reached; for example, the moment at which CO reaches a level of 4,000 ppm or the moment at which temperature reaches 100°C. A second way to define exposure limits is an integral approach. For some toxicants, particularly the asphyxiant gases such as CO and HCN, incapacitation or death occurs when the victim has inhaled a particular (concentration for a period of time, which is termed a toxic dose. In order to make some estimate of the likely toxic hazard in a particular fire, it is necessary to determine the point in time during the course of the fire exposure that the victim will have inhaled a toxic dose. This can be achieved by integrating concentration of toxicant under consideration over time. When the integral is equal to the toxic dose, the victim can be assumed to have received a dose capable of producing that toxic effect.

4.3.4 Review of Literature Related to Life Safety

The safe levels of exposure of the human population to fire effluent toxicants is discussed in detail by Purser [*Purser*, 1995; *Purser*, 1999]. A review of research related to establishing safe exposure limits is given by [*Peacock*, 1989]. Here, we will provide only a brief summary of the literature, and the reader is referred to these more complete documents. Our purpose is to identify the types of fire effluents known to cause adverse reactions in humans and to identify the range of values believed to be acceptable. Table 4-1 lists the tenability criteria identified and the threshold values found in the literature. A distinction is made between those that have potential to reduce visibility, cause incapacitation, and cause death. A second distinction is made between those values that are reported in the scientific literature and those that have been suggested as design values.

4.3.5 Temperature

Incapacitation and death can occur due to the affects of convected and radiated heat. Purser describes three ways in which heat may lead to incapacitation; through heat stroke (hyperthermia), skin pains and burns, or respiratory tract burns. However, the effects of temperature as an exposure limit under fire conditions has not been well studied. A search of the literature conducted by NIST in order to set tenability limits for its computer program, Hazard 1 [*Peacock*, 1989] reports that heat stress has been primarily studied in the industrial hygiene literature under conditions of prolonged exposure, typically 8 hours.

In fires, exposure temperatures are typically higher and exposure times shorter. Also in fires, the temperature at which adverse effects are noted depends not only on the exposure time but also on additional factors such as the relative humidity and the interaction of temperature with toxic gases. In the room of fire origin, the humidity level is high due to the production of water vapor from the fire. Human tolerance for heat decreases when exposed to air saturated with water vapor. There are no published studies to date on the combined effects of heat and toxic gases. The NIST Hazard 1 manual sets a limiting temperature due to incapacitation of 65°C and a limiting temperature for death at 100°C. The design value used for the original case study, is 150°C for five minutes [*Sullivan*, 1998].

4.3.6 Layer Height

Reduction in visibility as well as exposure to fire effluent gases and elevated temperatures occur when the hot upper layer descends to the head height of the occupants. Two heights that are meaningful to look at are 1.6 m above the floor and 0.91 m above the floor, corresponding roughly to the average height of an adult standing or walking and to a level above the ground that allows for crawling underneath the layer.

4.3.7 Visibility

The effects of smoke produced by a fire depend on the amount of smoke and on the properties of the smoke. Smoke emission is a function of the material burning and the combustion conditions under which smoke is produced – flaming, pyrolysis, and smoldering affect the amount and character of the smoke. Smoke production and properties are discussed in [*Mulholland*, 1995]. The smoke emission, together with the flow pattern, determine the smoke concentration as smoke moves throughout the building. Optically dense smoke affects exit choice and escape decisions, ability to find and/or follow a path of egress, and the speed of movement of the occupants. At an optical density (OD) of 0.2/m for irritant smoke and 0.5/m for non-irritant smoke, walking speeds have been shown to decrease from an average of 1.2 m/s to 0.3 m/s. Under these conditions people behaved as if they were in total darkness, feeling their way along the walls.

Purser found that smoke irritants consist of inorganic acid gases (such as hydrogen chloride) and organic compounds, particularly low molecular weight aldehydes, formaldehyde and acrolein. The yields of inorganic acid gases in fires depend mainly on the elemental composition of the materials being burned, while the yields of smoke and organic irritants depends mainly upon the decomposition conditions in the fire. In general, smoldering or vitiated fires tend to produce irritant smoke while well-ventilated flaming fires tend to produce non-irritant smokes. Purser suggests an optical density design tenability limit for buildings with small enclosures and travel distances of 0.2/m.

4.3.8 Asphyxiant Gases

Although smoke and irritant gases are likely to delay and inhibit escape attempts, they are unlikely to be the main cause of collapse or death during a fire. The main agents responsible for causing loss of consciousness in a fire are the asphyxiant gases. All asphyxiant gases cause incapacitation by impairing oxygen availability to the body tissues. Purser has done substantial research on identifying the important asphyxiant gases evolved from different materials involved in fires, determining how they interact to produce incapacitation and developing predictive models of time to incapacitation in fires [*Purser*, 1995; *Purser*, 1999]. His experiments have shown that only a small number of asphyxiant gases are important in fires. These are carbon monoxide, hydrogen cyanide, carbon dioxide, and reduced oxygen.

4.3.8.1 Carbon Monoxide

The best known of the asphyxiant fire gases is carbon monoxide. Carbon monoxide reduces the carriage of oxygen by hemoglobin in the blood and its release to the tissues. Carboxyhaemoglobin (COHb) remains in the blood for some time after exposure and is stable for many days, making determination of the extent of the exposure after the event possible.

The effects of carbon monoxide during a fire depend upon the dose inhaled over a period of time. A high concentration of CO inhaled for a short time can be equivalent to a low concentration inhaled over a longer time. Purser reports that incapacitation (loss of consciousness) occurs when an exposure dose of 25,000 ppm-min is achieved. Based on Haber's rule, which states that the toxicity depends upon the dose accumulated, this may be expressed approximately in terms of the concentration inhaled multiplied by the exposure time expressed in ppm-min. Other values have been reported or proposed in the literature for threshold values of carbon monoxide. The Hazard 1 manual reports an LC_{50} value for humans of 3,000 ppm CO based on a 30-minute exposure [*Peacock*, 1989]. Levin reports an LC_{50} value of 6,600 ppm based on a 30-minute exposure on rats [*Levin*, 1996].

Because of the many uncertainties in translating a 30-minute exposure value that causes death for 50% of the test subjects to a threshold concentration that causes zero deaths to the occupants, a range of design values have been used in the literature. These are shown in table 4-1.

4.3.8.2 Hydrogen Cyanide

Hydrogen cyanide is another asphyxiant gas that can be important in fires. Hydrogen cyanide is released in any fire of a fuel containing nitrogen, including acrylic fabrics, fire-retarded cotton fabrics, nylon, wool, and polyurethane foam. Some untreated materials such as wood, paper, and untreated cotton contain very little nitrogen and are not sources of cyanide in fires. The result is that most fires involving mixed materials are likely to produce greater or lesser amount of cyanide depending upon the main items involved and the fire conditions.

Unlike carbon monoxide, which stays in the blood as COHb, hydrogen cyanide, spreads rapidly into the tissues. This rapid transfer into the tissues has two effects. When a person is exposed to HCN in a fire, the concentration builds up rapidly in the blood, brain, and heart causing rapid collapse; thus, HCN is sometimes referred to as a "knock-down" gas. Purser reports that at concentrations of HCN up to around 100 ppm, time to incapacitation is around 20 minutes, but at concentrations approaching 200 ppm, the time to incapacitation is around 2 minutes. Also, once the cyanide disperses throughout body tissues, the HCN in blood drops, making post-analysis quantification of the exposure difficult. Hydrogen cyanide was not modeled for this case study; however, when building an input scenario generator, it is important to consider if the fuel sources contains nitrogen.

4.3.8.3 Carbon Dioxide

Another important gas is carbon dioxide, which acts mainly by causing an increase in the rate of uptake of other asphyxiant gases and by replacing O_2. Time to untenability based on carbon dioxide is not evaluated because it is reported that for carbon dioxide alone to be toxic, a single gas concentration of 470,000 ppm would have to be reached in a room. In a real fire, the highest theoretically possible concentration of CO_2 is 21%, a concentration that could occur only in the unlikely event that all the atmospheric O_2 was converted to CO_2. Therefore, CO_2 concentrations generated in fires are not lethal. However, CO_2 is a respiratory stimulant causing an increase in both respiratory rate and tidal volume. When combined with other gases such as carbon monoxide, CO_2 has a synergistic toxicological effect, i.e. the toxicity of the other gases are increased in the presence of CO_2.

4.3.8.4 Reduction in Oxygen

Oxygen deprivation is a special case of gas toxicity. The Hazard 1 manual suggests that incapacitation alone occurs when oxygen levels drop to approximately 10%. Levin suggests an LC_{50} value (for 30 minutes) for oxygen alone to be 5.4% [*Levin*, 1996].

4.3.9 N-Gas Model/ Fractional Effective Dose

Fire toxicologists believe that the observed effect of the exposure of animals and humans to the products generated by burning materials can be explained by the impact of the *combined* effect of a small number (N) of key gases actually released during combustion. Thus, these models are referred to as N-Gas models. There are different versions of the model; however, all models include the effects of carbon monoxide, carbon dioxide, hydrogen cyanide, and reduced oxygen. The combined effect of these gases is expressed using a parameter called Fractional Effective Dose (FED). The FED parameter calculates the time to a toxic dose of combustion gases, assuming that the total observed effect equals the sum of the effects of each of the component parts. If one receives 50% of a lethal dose of one gas and 50% of a lethal dose of another, death will occur. This has been demonstrated for CO and HCN. However, more work is needed to identify synergistic and antagonistic effects among gases.

Time to untenability due to the combined effect of the key fire gases modeled was calculated using both the Hazard 1 FED equation referred to in this document as "H-FED", and the FED equation suggested by Purser referred to in this document as "P-FED". The Hazard 1 equation is as follows:

$$(Hazard)FED = \sum \Delta t \left\{ \frac{\overline{C_{co}}}{\left(\frac{\overline{Cco} * 80000}{\overline{Cco} - 1700} \right) \left(\frac{100,000 - \overline{C_{co_2}}}{100,000} \right)} + \frac{\overline{C_{HCN}}}{3100} + \frac{9.2 - \overline{C_{o_2}}}{15.4} \right\} \tag{4.1}$$

Where $\overline{C_{co}}, \overline{C_{co2}}, \overline{Co_2}$ and $\overline{C_{HCN}}$ are the average concentrations over the time interval and Δt is the length of the time interval (min). For the Hazard 1 equation, death is assumed to occur at a H-FED value of one. Incapacitation is assumed to occur at a H-FED value of 0.5.

Purser also gives an equation to predict incapacitation due to exposure to a combination of fire gases.

$$(Purser)FED_{IN} = (FED_{ICO} + FED_{ICN})VCO_2 + FED_{IO} \qquad (4.2)$$

Where:

FED_{IN} = fraction of an incapacitating dose of all asphyxiant gases
FED_{ICO} = fraction of an incapacitating dose of CO
FED_{ICN} = fraction of an incapacitating dose of HCN
V_{CO2} = multiplication factor for CO2 induced hyperventilation
FED_{IO} = fraction of an incapacitating dose of low oxygen hypoxia

$$FED_{ICO} = (8.2925 \times 10^{-4} \text{ X ppm } CO^{1.036}) \text{ X } t/30 \qquad (4.3)$$

$$FED_{ICN} = ((\exp[CN]/43))t/220 \qquad (4.4)$$

$$VCO_2 = \exp([CO_2]/4) \qquad (4.5)$$

$$FED_{IO} = t/\exp[8.13 - 0.54(20.9 - \%O_2)] \qquad (4.6)$$

In the P-FED equation, a value of 1.0 indicates incapacitation. Death is expected to occur at two times that value. Purser suggests using a design value of 0.1 P-FED in order to allow for differences in sensitivity, to protect susceptible human sub-populations, and to allow for safe escape of nearly all exposed individuals.

4.3.10 Flashover

Flashover is a phenomena which occurs when a number of interrelated criteria reach critical values. These include an upper layer temperature of around 600°C. Because flashover is marked by the instantaneous ignition of all unburned fuel in the room, it serves as an upper bound for tenability.

4.3.11 Probabilistic Statement of Performance Selected for Design Analysis

Table 4-1 summarizes the performance criteria that will be used in the evaluation of the design fire scenarios. Cumulative distribution functions for probability vs. time to untenability are constructed for the various tenability criteria and threshold values. From these, insights can be drawn for all four elements of probabilistic design statements. These results are presented in Chapter 5.

Table 4-1. Performance Criteria and Threshold Values

Performance Criteria	Threshold Incapacitation	Threshold Death	References
Temperature	65°C	100°C 150°C, 5 min	Hazard 1 Sullivan, design
Layer height	1.6 m 0.91 m		Head height Crawl height
Smoke optical density	0.5/m 0.2/m		Purser, darkness Purser –design
CO	25,000 ppm-min 1,500 ppm 2,000 ppm, 5min	 3,000 ppm 6,600 ppm	Purser Stroup – design Sullivan – design Hazard 1 Levin
O2	10%	 5.4%	Hazard 1 Levin
FED	0.1 1.0 0.5	 2 1	Purser eqn. Design Purser eqn. 4.2 Hazard 1 eqn. 4.1 Purser eqn. 4.2 Hazard 1. eqn 4.1
Flashover		600°C	

4.4 *Step 5.* Development of Distribution of Design Fire Scenarios

One of the most important elements of a performance-based design is the specification of the fire scenarios. As defined in the Guide to Performance-Based Analysis and Design for Buildings [*SFPE*, 1999], design fire curves are an engineering description of the development of a fire. Design-fire curves are time based and establish a relationship between the heat release rate of the fire and time. Design fire curves are a vital part of the technical or engineering manifestation of design-fire scenarios.

The full design fire scenario is made up of the design fire curve along with building and occupant characteristics. Building characteristics include architectural features and construction of the compartments of interest as well as interconnections between compartments. In the performance-based design process without uncertainty, the stakeholders agree on a small number of design fire scenarios. In the performance-based design process with uncertainty, the design fire curves are established but also a statistical likelihood is assigned to each curve, creating a distribution of design fire curves. Steps 5 – 5e describe the building of a random scenario generator used to develop a number of design fire scenarios.

The generation of a set of design fire scenarios involves defining distributions for and correlations among each of the uncertain input parameters identified in Step

5b, creating an input scenario generator, selecting a sampling method, and determining the number of scenarios to calculate. Figure 4-2 shows the process used for this case study.

As shown in the figure, the output from the input scenario generator is a number of CFAST input files. Software was written to automatically generate input files in the correct format for CFAST. Additional software was written to run these files in batch mode and to generate output files.

The generation of a set of design fire scenarios for the case study has two purposes. One is to demonstrate the use of the methodology for the quantitative treatment of uncertainty, and the other is to answer questions regarding the effect of variations in the input parameters on the predictions of the fire model. When faced with a choice of representation of the input parameters to be accurate to this specific building, or to address research questions, allowances in accuracy to the case study were made. Thus, results are representative but should not be used in decision making for this specific building. Application of the methodology to a real building was part of the iterative process of methodology development and refinement. Lessons learned from this iterative process are discussed in Chapter 7.

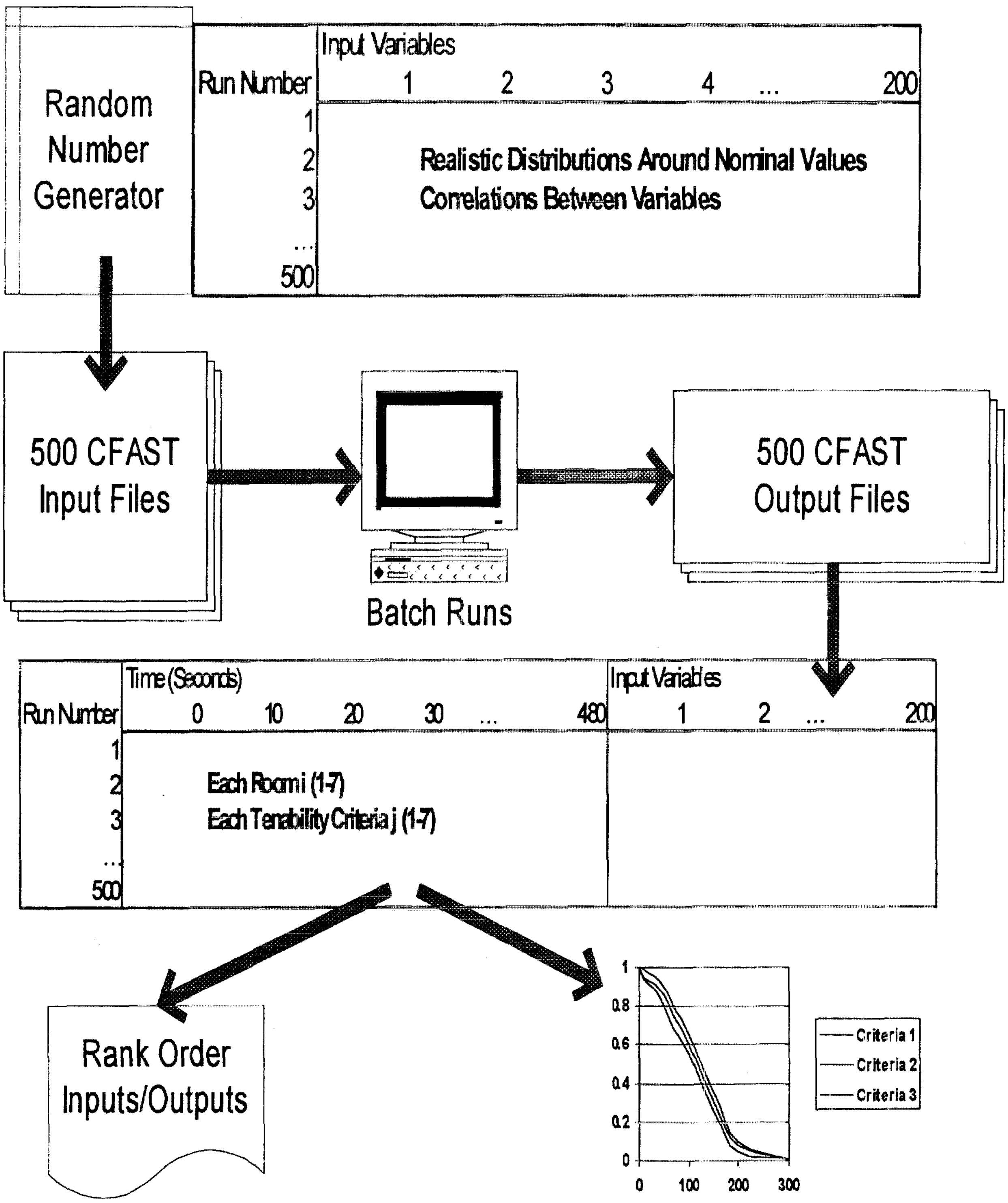

Figure 4-2. Process Diagram for Case Study

4.5 *Step 5a.* Selection and Engineering Overview of Calculation Procedure

4.5.1 Selection of a Fire Model

A mathematical model was needed that was capable of dealing with multiple rooms and ventilations since the design being investigated has seven rooms with twelve doors and windows. In addition, a model was needed that would provide an estimation of temperature and thickness of the hot upper layer, estimation of species concentrations, estimation of the time to flashover, and an indication of the visibility for each compartment. A choice between the faster run times of a zone model and the increased resolution of a field model must be made for a given design.

For this case study, it was determined that the assumptions underlying a zone model would be adequate to model these average size rooms and that a field model was not needed. The calculation procedure selected here is the deterministic computer fire model CFAST, a multi-room enclosure zone fire model that is a product of the National Institute of Standards and Technology. [Peacock, 1997].

The NFPA Fire Protection Handbook [*Walton and Budnick*, 1991] and the SFPE Handbook of Fire Protection Engineering [*Walton*, 1995] both provide overviews of the leading enclosure zone fire models. The enclosure zone fire models ASET [*Walton*, 1985], and FIRST [*Mitler and Rockett*, 1987] are single-room enclosure fire models. COMPBRN III is based on an assumption of fires involving large fuel loads and is used for the assessment of risk in the nuclear power industry. COMPF2 [*Babrauskas*, 1979] and CSTBZ1 are enclosure zone fire models for calculating characteristics of post-flashover fires. Other enclosure zone fire models such as FPETOOL [*Nelson*, 1990] and FASTLite rely on greatly simplified engineering models. LAVENT is a program developed to simulate the environment and the response of sprinkler elements in compartment fires with draft curtains and fusible-link-actuated ceiling vents. [*Cooper*, 1990]

Thus CFAST was selected because it is the best currently supported enclosure zone fire model capable of handling this multi-room, multi-vent simulation and predicting the many key outcomes needed for evaluation of the performance-based designs. In addition, CFAST is used internationally to conduct performance-based fire engineering calculations, it was used in the original performance-based design of this building, and access to the source code for CFAST was available through NIST. Full documentation for CFAST is available in two publications, a technical reference guide [*Jones et al.*, 2000] and a user's guide [*Peacock et al.*, 1997].

4.5.2 History of CFAST and Enclosure Zone Modeling at NIST

In 1983, NIST began development of the enclosure zone fire model FAST [*Jones*, 1985]. This was the first implementatijon of a zone model using a complete set of ordinary differential equations for the conservation of mass, energy, and momentum. This provided for a faster and more robust solution to the problem of fire growth and smoke transport. It included potential for free burn and vitiated fires in the lower and upper layers as well as through doors and windows, however, it was limited to six rooms because of computer memory limitations at that time. In 1985, NIST began development of the enclosure zone fire model CCFM [*Cooper and Forney*, 1990a; *Cooper and Forney*, 1990b]. CCFM was a well-structured two-layer zone model. Through the 1980's and 1990's, many advances in enclosure zone fire modeling were made at including increasing the number of possible compartments to 15, mechanical ventilation, entrainment into lower layers, multiple fires, and external wind. In 1989, a complete hazard assessment methodology , Hazard 1 was released accompanied by software that included the enclosure model FAST as well as special purpose models to calculate egress time, time to activation of detectors, and time to untenability. In 1990, the restructured FAST became CFAST, which was functionally equivalent to FAST. FAST is now the name for an interactive program used to generate input data files for and run the CFAST model.

4.5.3 Engineering Overview of CFAST

CFAST is a deterministic model capable of predicting the environment in a multi-compartment structure subjected to a fire. It calculates the time evolving distribution of smoke and fire gases and the temperature throughout a building during a user-specified fire. CFAST is a member of a class of models referred to as zone models. In a Zone model, each room is divided into a small number of volumes (called layers), each of which is assumed to be internally uniform. That is, the temperature, smoke and gas concentrations within each layer are assumed to be exactly the same at every point. Specifically in CFAST, each room is divided into an upper and lower layer. This assumption is based on experimental observations that in a fire, room conditions do stratify into two distinct layers. While variations in conditions within a layer can be measured, these are generally small compared to differences between the layers. (This assumption is less valid in large volume, high ceiling height spaces as is shown in [*Davis et al.*, 1996; *Notarianni and Davis*, 1993].)

CFAST solves a set of equations that predict state variables (e.g. pressure and temperature) based on the conservation of energy, mass, and momentum, plus the ideal gas law.

4.5.3.1 Fires

Within CFAST, the fire converts the fuel that is burned into enthalpy from the heat of combustion and products from the yield of a particular species as a conversion factor. The rate at which burning occurs must be specified as an input parameter. Where insufficient oxygen is entrained into the fire plume, unburned fuel will successively move into and burn in the upper layer of the fire room; the plume in the doorway to the next room; the upper layer of the next room; the plume in the doorway to the third room; and so forth until it is consumed or gets to the outside.

Similar to other current fire models, CFAST includes no a combustion model and is unable to predict fire growth or species production rates.

4.5.3.2 Plumes and Layers

Above any burning object, a plume is formed which is not considered to be a part of either layer, but which acts as a pump for enthalpy and mass from the lower layer into the upper layer. Figure 4-3 shows a plume from a chair fire and the formation of the hot upper layer. The other source of mixing between the layers occurs at vents such as doors and windows. Here, there is mixing at the boundary of the opposing flows moving into and out of the room. CFAST uses empirically derived correlations to determine the amount of mass moved between layers by the plume and to determine the degree of mixing.

Examples of phenomena which are not included in CFAST are sources of convection such as radiators or diffusers of heating and air conditioning systems, and the downward flows of gases caused by cooling at the walls, which causes mixing. Also, the plumes are assumed not to be affected by other flows that may occur. For example, if a burning object is near a door, the strong inflow of air would cause the plume axis to lean away from the door and affect entrainment of gases into the plume. This phenomena is not considered in CFAST.

Each room is divided into two layers, the upper and lower. At the start of a simulation, the upper layer volume is near zero. As enthalpy and mass are pumped into the upper layer by the fire plume, the upper layer expands in volume, causing the lower layer to decrease in volume and the interface to move downward. If the door to the next room has a soffit, there can be no flow through the vent from the upper layer until the interface reaches the bottom of that soffit. In the early stages, the expanding upper layer will push down on the lower layer air and force it into the next compartment through the vent by expansion.

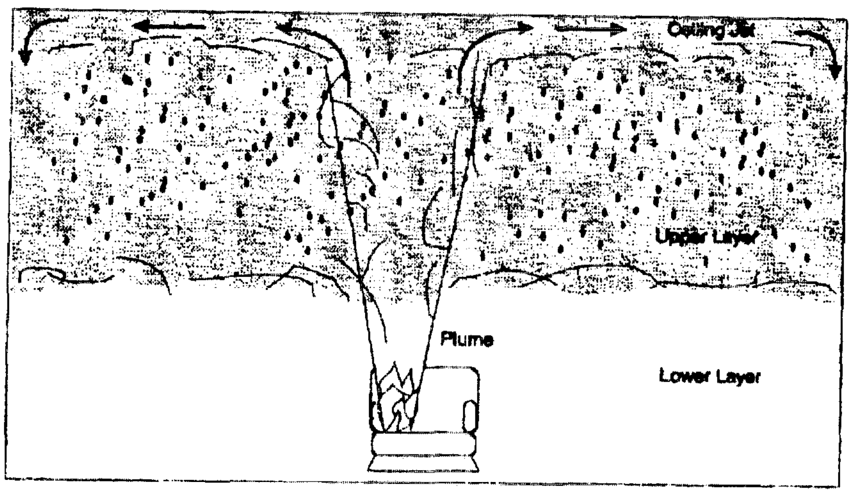

Figure 4-3. Two-Layer Enclosure Zone Fire Model

Once the interface reaches the soffit level, a door plume forms and flow from the fire room to the next room is initiated. As smoke flow from the fire room fills the second room, the lower layer of air in the second room is pushed down, pushing some of this lower layer air back into the fire room. Thus, a vent between the fire room and connecting rooms can have simultaneous, opposing flows of air. All flows are driven by pressure differences and density differences that result from temperature differences and layer depths. Thus, the key to getting the right flow is to correctly distribute the fire's mass and enthalpy between the layers.

4.5.3.3 Vent Flow

Flow through vents is governed by the pressure difference across a vent. There are two situations that give rise to vent flow. The first is that of air or smoke which is driven from a compartment by buoyancy. The second type is due to expansion, which is particularly important when conditions in the fire environment are changing rapidly. Flow through vents is the dominant phenomenon in a fire model because it fluctuates most rapidly and transfers the greatest amount of enthalpy on an instantaneous basis of all the source terms.

4.5.3.4 Heat Transfer

Heat transfer is the mechanism by which the gas layers exchange energy with their surroundings. Convective heat transfer occurs from the layers to the room surfaces. The heat transferred in the simulations conducts through the wall, ceiling, or floor in the direction perpendicular to the surface conduction parallel to the wall is not considered. CFAST allows different material to be used for the ceiling, floor, and walls of each room. Material thermophysical properties are assumed to be constant, although it is known that they actually vary with temperature. This assumption is made because data over the required temperature range is scarce even for common materials; and because the variation is relatively small for most materials.

Radiative heat transfer occurs among the fire, gas layers and compartment surfaces. This transfer is a function of the temperature differences and the emissivity of the gas layers as well as the compartment surfaces. For the fire and typical surfaces, emissivity values only vary over a small range. For the gas layers, however, the emissivity is a function of the concentration of species which are strong radiators, predominately smoke particulates, carbon dioxide, and water.

Errors in the species concentrations can thus give rise to errors in the distribution of enthalpy among the layers, which results in errors in temperatures, causing in errors in the flows. This illustrates just how tightly coupled the predictions made by CFAST are.

4.5.3.5 Species Concentrations and Deposition

Each layer starts out initially composed of air at a temperature specified by the user. As fuel is pyrolyzed, the various species are produced in direct relation to the mass of fuel burned (this relationship is the user-specified species production rate per mass of fuel burned). These include carbon dioxide, carbon monoxide, water, soot, hydrogen cyanide, and hydrogen chloride.

Each unit mass of a species produced is carried in the flow to the various rooms and accumulates in the layers. The model keeps track of the mass of each species in each layer and knows the volume of each layer as a function of time. The mass divided by the volume is the mass concentration, which along with the molecular weight, gives the concentration in volume percent or ppm.

4.5.3.6 Assumptions and Limitations

As can be seen from the descriptions of the various fire phenomena in CFAST, fire modeling involves an interdisciplinary consideration of physics, chemistry, fluid mechanics, and heat transfer. In some areas, fundamental laws can be used, whereas in others empirical correlations must be employed to bridge gaps in existing knowledge. The necessary approximations required by operational practicality result in the introduction of uncertainties in the results. The user must understand the inherent assumptions and limitations of the program and use these programs judiciously in order to make meaningful estimates of these uncertainties.

4.5.4 Mechanics of Running CFAST

As with any computer calculation, the quality of the calculated result is directly related to the quality of the inputs provided by the user. CFAST is intended for use only by those competent in the field of fire safety and is intended only to supplement the informed judgement of the qualified user. However, developing appropriate inputs for a realistic simulation of typical fire scenarios can be an imposing task. Default values are provided for some of the input parameters; however, little or no additional information is provided to the user to aid in the selection of input values. Inputs can be entered via the creation of an input file or through a graphical user interface. The many inputs needed to run CFAST are described below, and justification is provided for treating them as certain or uncertain. CFAST runs on a desktop computer in MS-DOS. Run times vary from a few minutes to many hours.

4.6 *Step 5b.* Identification of Uncertain Input Parameters

The number of user-specified inputs to run a single-design fire scenario is dependent upon many factors such as the number of compartments, the number of doors and windows, and the length of the simulation. For the seven room apartment layout being studied here, a typical data file (one set of input parameters to run one design fire scenario) for CFAST approximately 450 input specifications. After reviewing each input, 203 were identified as having uncertainty and/or variability worthy of investigation in the full analysis.

These parameters can be classified into seven categories. The categories are weather, building geometry, ventilation, building materials, fire variables, products of combustion, and chemistry. Weather parameters include factors such as internal and external temperature and pressure, wind, and relative humidity. For the weather data, the goal was to capture the monthly variability in each parameter and to correlate the different parameters.

Building-geometry parameters describe the apartment layout and dimensions of each of the compartments; the interest here is the effects on key outcome criteria of small variations in geometry. Ventilation parameters describe the connections between compartments such as doors and windows and connection between a compartment and the outside. By varying the opening position of doors and windows, we should be able to quantify the effect of ventilation on key fire parameters.

Fire variables include the growth rate constants described in Step 5c, the heat of combustion, the radiative fraction, and the location and position of the fire. Products of combustion include the rates of generation of chemical species per amount of fuel burned. Chemistry variables include gas ignition temperatures, lower oxygen limits, and molecular weight. Parameters such as the chemistry variables and the heat of combustion are often left by the design engineer at their default values. One goal of this study is to determine the effect of changes in these values. Each of the input parameters and its mathematical representation is detailed in the next section.

4.7 Step 5c. Generate a Distribution of Design Fire Curves

The growth rate of an upholstered furniture fire may be quite fast. Upholstered couches have been measured reaching a peak heat release rate of 5,125 kW in just 175 seconds from ignition. Other items may burn slower such as a metal frame chair with minimum cushion or a plywood bookcase with an aluminum frame.

NIST has developed a large-scale calorimeter for measuring the heat release rates of burning furniture. Staff burned over 40 items of furniture and measured the heat release rates over time. Differences in the burning characteristics were in terms of the peak heat release rate and in the time to reach the peak rate [*Lawson et al.*, 1983]. Many of these fires, were found to follow a quadratic growth rate, with the heat release rate, Q, given by:

$Q = \alpha t^2$

where: Q is in kW, t is the time from ignition in seconds and α is the fire growth rate constant. Based on the results of these tests, values of α were used to define slow, medium, fast, and ultrafast growth rate fires as shown in Table 4-2. The corresponding heat release rates over time are shown in Figure 4-4.

Table 4-2. Design Fire Growth Rates

Fire Growth Rate	α	**Likelihood Of Occurrence**
Slow	0.00293	0.20
Medium	0.01172	0.50
Fast	0.04689	0.25
Ultra fast	0.18756	0.50

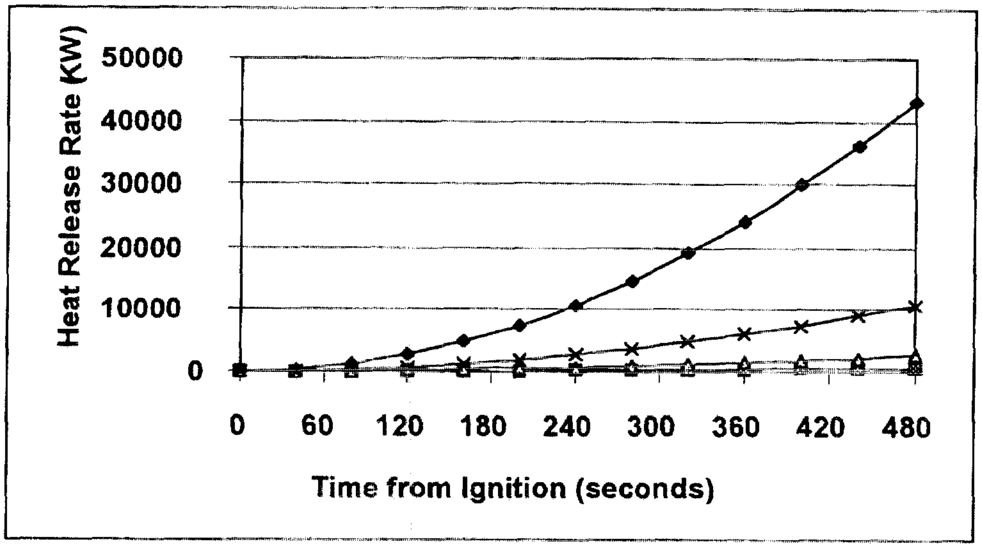

Figure 4-4. Design Fire Curves

It is impossible to know *a priori* what the rate of fire growth will be. Educated guesses can be made based on statistics provided on the item first ignited; however, as the NIST studies show common furniture such as mattress and bedding, upholstered furniture, and bookcases may burn slowly or rapidly as a function of many non-intuitive factors. When conducting an analysis for a specific building, a range of design fires should be used.

4.8 Step 5d. Define Distributions of and Model Correlations Among Other Input Parameters

This section describes an important step in the generation of a set of design fire scenarios. Each variable identified in Step 5b as having potentially significant uncertainty is assigned a distribution. These distributions are based on a combination of the fire-protection literature, experimental data, observations, judgement, expert elicitation, and modeling.

4.8.1 Weather Module

In the weather module, a month of the year is randomly selected. For that month, a value is sampled from a normal distribution for external temperature taken from National Weather Service data. Temperature is correlated to external pressure, wind, relative humidity, opening of windows/doors, internal temperature and pressure, and initial fuel temperature. A correlated vector of weather values is generated.

Correlations used in the weather module were determined through an expert elicitation of a climatologist [*Ribesy*, 1999]. Table 4-3 shows the results of that elicitation. The computer program @RISK was then used to generate a set of correlated values for temperature, pressure, wind, and relative humidity. The values generated were then used in the input scenario generator. Table 4-4 shows the representation of the weather variables in the input scenario generator.

Table 4-3. Correlation Coefficients for Weather Parameters

	TEMP	PRESSURE	WIND	HUMIDITY
Temp	1	0.3	-0.5	0.7
Pressure	0.7	1	-0.7	0.5
Wind	-0.6	-0.6	1	-0.5
Humidity	0.7	0.7	-0.5	1

4.8.2 Building Geometry Module

The second module is the building geometry module. Many of the dynamics of the buildup and spread of heat and products of combustion in a building subject to a fire are a function of the building layout and the individual compartment sizes. Thus, many of the calculations in CFAST use as inputs aspects of the compartment dimensions and the dimensions of the vent openings to other rooms. Sensitivity of the critical outcome criteria to varying room dimensions and vent dimensions +/- 10% was studied in order to determine if a similar apartment with slightly different dimensions would require a separate simulation. Table 4-5 shows the input distributions for each parameter.

4.8.3 Ventilation Module

The ventilation module contains parameters that describe the percent openings of each vent. A value of one indicates a fully open vent. A value of 0.5 indicates a half-open vent and a value of 0.1 is used for a closed vent with some leakage. Vents 6,7, and 9 are windows to the outside of the building. For this case study, percent opening of the windows is correlated to the month of the year. The windows are assumed open in spring and fall and closed in the winter. Opening position of other vents is random as specified in Table 4-5.

Table 4.4 Weather Module

VARIABLE	NAME	RANGE/FORMULA	CORRELATIONS	SOURCE
Internal temperature, K	INTEMP	Uniform (286-295.4)	INTPRESS	Engineering judgement
Internal pressure, Pa	INTPRESS	Uniform (101300, 107300)	INTEMP	
External temperature, K	EXTEMP	Based on distributions for month	EXPRESS, WINDSPD, CHRH, MONTH	National Weather Service Data
External pressure, Pa	EXPRESS	Pressure in Pa from the @Risk simulations	EXTEMP, WINDSPD, CHRH, MONTH	
Wind speed, m/s	WINDSPD	Based on month and @risk	EXTEMP, EXPRESS, WINDSPD, MONTH	
Cosine of angle between wind direction and vent opening	WIND6, 7,9,12	Uniform (-1,1)	Uncorrelated	
Percent opening of vents to outside (windows)	CV6, CV7, CV9	Based on month, see table 4-6	MONTH	Limits allowed in CFAST
Month of year[i]	MONTH	Uniform (1,12)	Window	Dummy Variable
Relative humidity, %	CHRH	IF(uniform(0,1)<0.8,ROUND(uniform (0,1)*10+50,0),(uniform(0,1)*100,0))	EXPRESS EXTEMP WINDSPD	
Initial fuel temp, ^{0}K	CHIFT	Equal to internal temperature	INTEMP	

[i] Month of the year is used here as a dummy variable. It is not an input parameter to CFAST

4.8.4 Building Materials Module

Each construction material possesses its own set of thermo-physical properties such as specific heat, emissivity, and density. Although the construction materials for this specific building are known, it is important to know how predictions are affected by changes in building materials. Several different common building materials that might be found in an apartment building were selected for evaluation in the input scenario generator. For a given design scenario, once a material is selected for a building component, (e.g. wall material), that material is used in all compartments. The materials evaluated in this study are concrete, gypsum, hardwood, cellulose, and gyplast. Table 4-7 shows their representation in the input scenario generator.

4.8.5 Fire Parameters Module

For the case study, statistics were gathered for residential buildings and in particular for apartment buildings. The NFPA publishes data for apartment buildings on room of origin of apartment fires [Hall, 1994 #56]. Table 4-8 summarizes this data relevant to our case study.

The fire location in the room was allowed to vary randomly across the full x- and y- dimensions of that room; the fire location was assigned a higher likelihood of being in the bottom half of the room. The heats of combustion were taken from the fire literature for the material burning. Table 4-9 shows the representation of these parameters in the input scenario generator.

4.8.6 Products of Combustion Module

These parameters describe the composition of the pyrolyzed fuel. The CO parameter is the ratio of the mass of carbon monoxide to carbon dioxide produced by the oxidation of the fuel in units of kg/kg. The OD parameter is the ratio of the mass of carbon to carbon dioxide produced by the oxidation of the fuel. These values used for each of these parameters represent production rates for wood, plastic, and foam reported in the literature. Values of CO, OD, and heat of combustion are correlated by material burning. [*Tewarson*, 1995]

4.8.7 Chemistry Module

The chemistry module contains the lower oxygen limit (LOL), the gas ignition temperature (GIT), and the molecular weight of the fuel vapor. The LOL is the limit on the ratio of oxygen to other gases in the system below which a flame will not burn. The GIT is the minimum temperature for ignition of the fuel as it flows from a compartment through a vent into another compartment. The molecular weight refers to the weight of the fuel vapor. These parameters are user-specified inputs; however, in design practice, these are normally left at the program default values. Therefore, it is of interest to know how changes in the value of these parameters affect predictions of key outcome criteria. Table 4-11 shows the representation of the chemistry parameters in the input scenario generator.

Table 4-5 Building Geometry Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Width of each room	WIDTH1,....WIDTH7	+/- 10% of dimension	Building geometry parameters are uncorrelated	Room dimensions locations of door and windows, etc. taken from original case study
Depth of each room	DEPTH1.....DEPTH7	+/- 10% of dimension		
Height of each room	HEIGHT1...HEIGHT7	90% =2.44; 10% = uniform (2.39,2.49)		
With of vent	HVWTH1...HVWTH12	+/- 10% of vent width		
Height of soffitt	SOFFITT1...SOFFITT1 2	+/- 10% of soffitt height		
Height of windowsill	SILL1, SILL4, SILL6-7, SILL7, SILL9	+/- 10% of dimension		

Table 4-6 Ventilation Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Percent opening of windows to outside	CV6, CV7, CV9	Open spring and fall (1.0) Closed summer and winter (0.1)	Month of year	Assumed open spring and fall, closed summer and winter
Percent opening of other vents	CV1 to CV5, CV8, CV10-CV12	40% probability of being closed with 10% leakage(0.1) 30% probability of being open (1.0) 30% probability of being partially open (0.5)	Not correlated	Assumed

Table 4-7 Building Materials Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Ceiling Materials	CEILI1....CEILI7	20% concrete 20% gypsum 20% hardwood 20% cellulose 20% gyplast	Correlated to materials used in other compartments	Selected common building materials for residential high-rise apartment buildings, values of thermo-physical properties from CFAST database
Wall Materials	WALLS1....WALLS7			
Floor Materials	FLOOR1...FLOOR7	50% concrete 25% hardwood 25% cellulose		

Table 4-8. Room of Origin of Apartment Fires

ROOM OF ORIGIN	% OF FIRES ORIGINATING HERE
Living room	9%
Balcony	10%
Bedroom	13%
Kitchen	30%
Bathroom	10%
Entranceway	10%
Corridor	18%

Table 4-9 Fire Parameters Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Heat of Combustion, J/kg	CHHOC	50% 8500000 20%15000000 25% 9000000 5% 20000000	OD, CO	[*Tewarson*, 1995]
Radiative Fraction		60% 0.25 40% uniform (0.15,0.35)	Uncorrelated	SFPE Handbook
Heat Release Rate, Watts[ii]	Q = alpha*t^2	alpha slow = .00293 (20%) med = .01172 (50%) fast = .04689 (25%) ultra fast = .18756 (5%)	Uncorrelated	
Origin	ORIGIN	See table 4-8 above	Uncorrelated	NFPA statistics
x-position, y-position, m	FPOSX, FPOSY	For each room, uniform distribution across full depth and width	Uncorrelated	Fire position varies over the range of x and y coordinates of the room
z-position, m	FPOSZ	90% uniform (0,1) 10% rand()*1.95m	Uncorrelated	Assumed based on statistics and judgement, more fires in lower half of room

[ii] heat release rate could be correlated with first item ignited

Table 4-10 Products of Combustion Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Kg toxic combustion products/ kg fuel pyrolyzed	CT	20% 0.1 80% 1.0 20% 0.1	uncorrelated	[*Peacock*, 1989]
Ration of CO/CO_2	CO	50% 0.0035 20% 0.0174 25% 0.95 5% 0.016	OD	[*Tewarson*, 1995]
Ratio of C/CO_2	OD	50% 0.015 20% 0.041 25% 0.1655 5% 0.1105	CO	[*Tewarson*, 1995]

Table 4-11 Chemistry Module

VARIABLE	NAME	RANGE OR FORMULA	CORRELATIONS	SOURCE
Lower oxygen limit	LOL	Uniform (6,12)	Uncorrelated	Varied around default of 10
Gas ignition temperature	GIT	CHIFT + Uniform (-20,50)	Initial fuel temperature	Varied around initial fuel temperature
Molecular weight	MW	Uniform (7,13)	Uncorrelated	Varied around default of 16

4.9 Step 5e. Selection of Sampling Method and Determination of Number of Scenarios

For this study, a Monte Carlo analysis was used. The input scenario generator was built mainly in Excel. Modules with multiple correlated variables such as the weather module were built in @RISK, and the sets of values generated were then transferred to the input scenario generator in Excel.

Initially, 40 prototype test scenarios were conducted and analyzed. Subsequently, 500 scenarios were used in this study to generate statistics to ensure the sampling method was operating properly. Calculation time per scenario ranged from under one hour to over 18 days, with a total time of 6 months required to complete the final 500.

4.10 *Step 6*. Development of Candidate Designs

For this case study, there are four candidate designs. Design 1 is the case with no sprinklers. Design 2 has fire sprinklers in the corridor only, and Design 3 has sprinklers in the corridor and a quick-response sidewall sprinkler head in the entranceway of the dwelling unit. Design 4has sprinklers in the corridor, entranceway and kitchen. Sprinkler heads are rated for an activation temperature of 57°C and have a response time index of 50 $((m\text{-}s)^{1/2})$. The response time index is a measure of the thermal mass of the sprinkler element.

These four sprinkler options are meaningful for this building due to cost considerations. In lieu of a full retrofit of an automatic sprinkler system, which is very expensive, the building owner wants to evaluate the effectiveness of a partial sprinkler system. One option would be to sprinkler the corridor only. This should improve the probability of safe egress for the occupants. Another option is to sprinkler the entranceway of each apartment in addition to the corridors. The entranceway is a common point to all egress routes and is relatively less expensive to sprinkler during a retrofit than other areas of the apartment. In addition, installation of automatic sprinklers in the kitchen may be necessary to meet the probabilistic statement of performance because approximately 30% of fires originate in the kitchen.

4.11 Running the Scenarios

The 500 design fire scenarios calculated for this case study had a wide range of run times. Several of the scenarios ran in less than a minute and some took over one week to finish. None of 500 scenarios crashed. The scenarios were run in batch mode. Several programs were written at NIST to automate the process of 1) creating CFAST input files from the numbers in the input scenario generator, 2) running the CFAST files in batch mode and creating CFAST output files, and 3) generating Excel spreadsheets for data analysis.

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THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

5. RESULTS FROM APPLICATION TO CASE STUDY

5. RESULTS OF THE CASE STUDY

This chapter presents results from the 500 scenarios calculated for this case study. It parallels Steps 7d –10 of Table 3-1, the Performance-Based Design Process with Uncertainty. As discussed in Section 4.3, studies are needed on the sensitivity of time to untenability as a function of different performance measures and different critical threshold levels for these measures. Section 5.1 demonstrates concepts related to performance criteria through discussion of sensitivity of time to threshold values of temperature. Section 5.2, addresses six other performance criteria discussed in Section 4.3 and for each performance criterion evaluated, measures of sensitivity to the threshold value are determined. Knowing the sensitivity of predictions of time to untenability (time available for safe egress) is important to establishing policy for the four elements of a probabilistic statement of performance, performance criteria, threshold values, probability, and time.

In Section 5.3, we look at the base case for this study, which is Design 1, (no sprinklers). An egress analysis is conducted for the base case, and in Section 5.4, the probability vs. time to untenability for the base case is compared to the probability vs. time to untenability for Design 2, (sprinklers in the corridor), Design 3, (sprinklers in the corridor and entranceway), and Design 4 (sprinklers in the corridor, entranceway, and kitchen). In Section 5.5, the uncertainty importance of the input variables is evaluated. An uncertainty importance analysis provides information that can help simplify future analyses, aid in the establishment of research priorities, and suggest targeted improvements to the models. Sections 5.6 and 5.7 discuss evaluation of the acceptability of each of the candidate designs, selection of a final design and documentation.

5.1 *Step 7d.* Cumulative Distribution Functions for Time to Untenable Temperature and Sensitivity to Threshold Values

Figure 5.1 shows a cumulative distribution function (CDF) of time to untenability based on a performance criterion of 100°C in the upper layer. The CDF of time to untenability is constructed from the 500 CFAST predictions of upper layer temperature using the procedure described in Section 3.10.2.

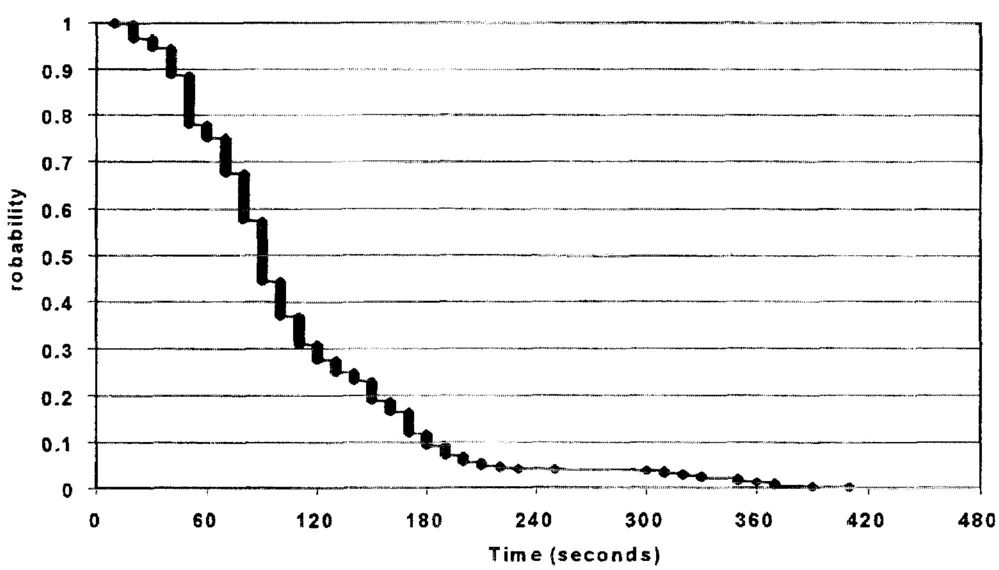

Figure 5-1. Minimum Time to 100°C (seconds)

Figure 5-1. shows a 0.9 probability of having 40 seconds or more until 100°C is reached in the upper layer and a 0.5 probability of having 90 seconds or more.

Sensitivity of time to untenability based on the threshold value of temperature is indicated in Figures 5-2 – 5-4. In Figure 5-2, the CDF for a performance criterion of 100° C is compared to the CDF for performance criteria of 65°C and 150°C . Here, consistently, the time to untenability in the room of origin is roughly double at the 150°C threshold than it is at the 65°C threshold. At the 0.9 probability level the time to reach 65°C is 30 seconds compared to 60 seconds to reach 150°C. At the 0.5 probability level, the time to reach 65°C is 70 seconds compared to 120 seconds to reach 150°C.

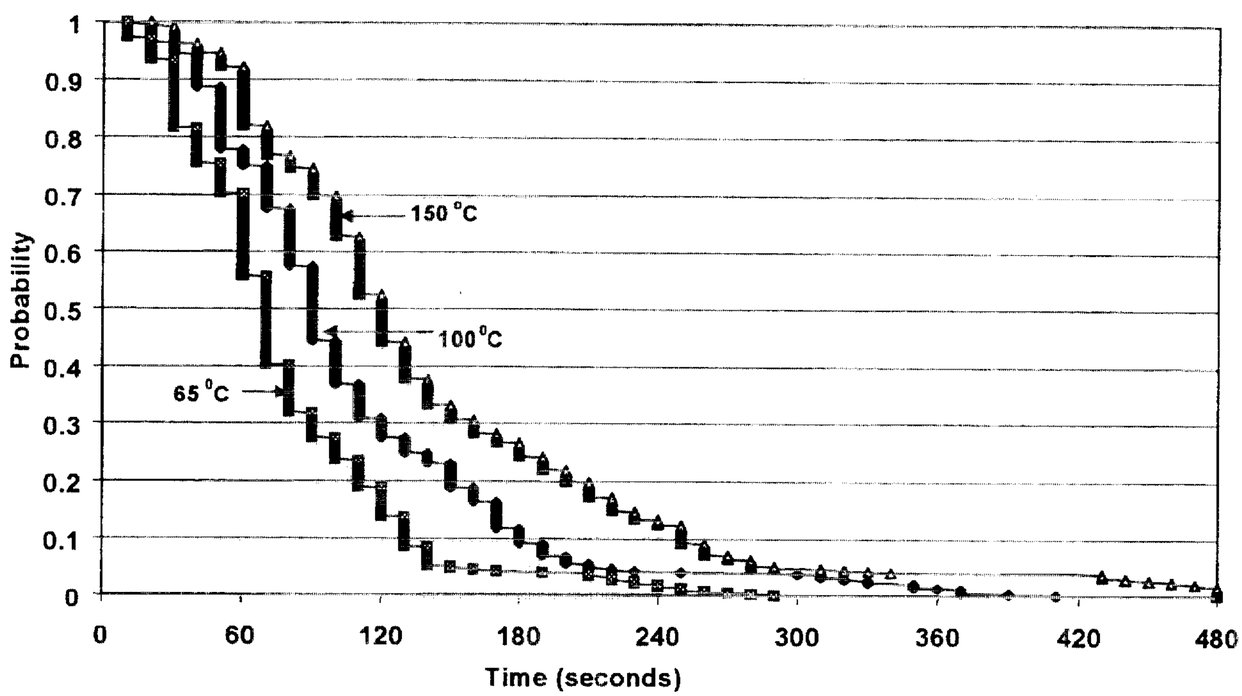

Figure 5-2. Time to Threshold Temperature

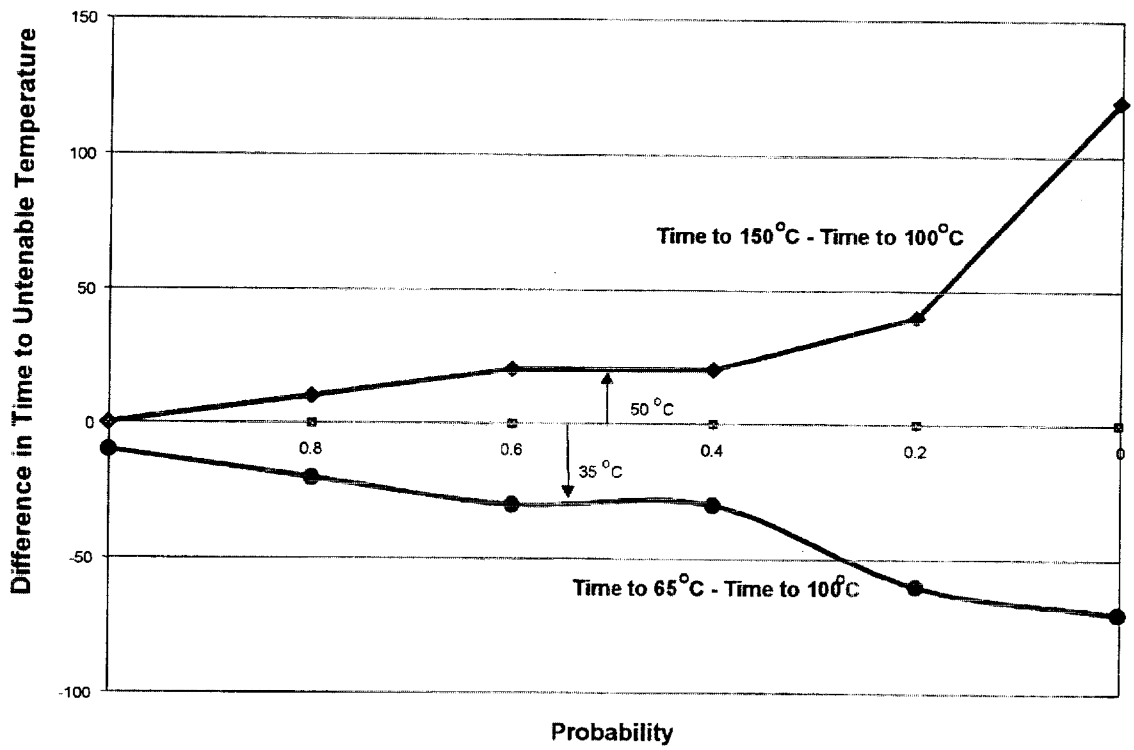

Figure 5-3. Sensitivity of Time to Untenability as a Function of Threshold Temperature

In Figure 5-3, sensitivity of the difference in time to a threshold temperature of 65°C and 150°C relative to the time to reach 100°C is shown as a function of probability. It is important to note that the significance in selecting one temperature threshold over another decreases as the probability increases. For example, if we chose to make fire-safety decisions at the 0.9 probability level, the difference in time to reach a threshold temperature of 65°C, typically representative of an incapacitation, and the time to reach a threshold temperature of 100°C, typically representative of lethality, is only 10 seconds. At the 0.5 probability level, this difference is only 20 seconds. The implication is that

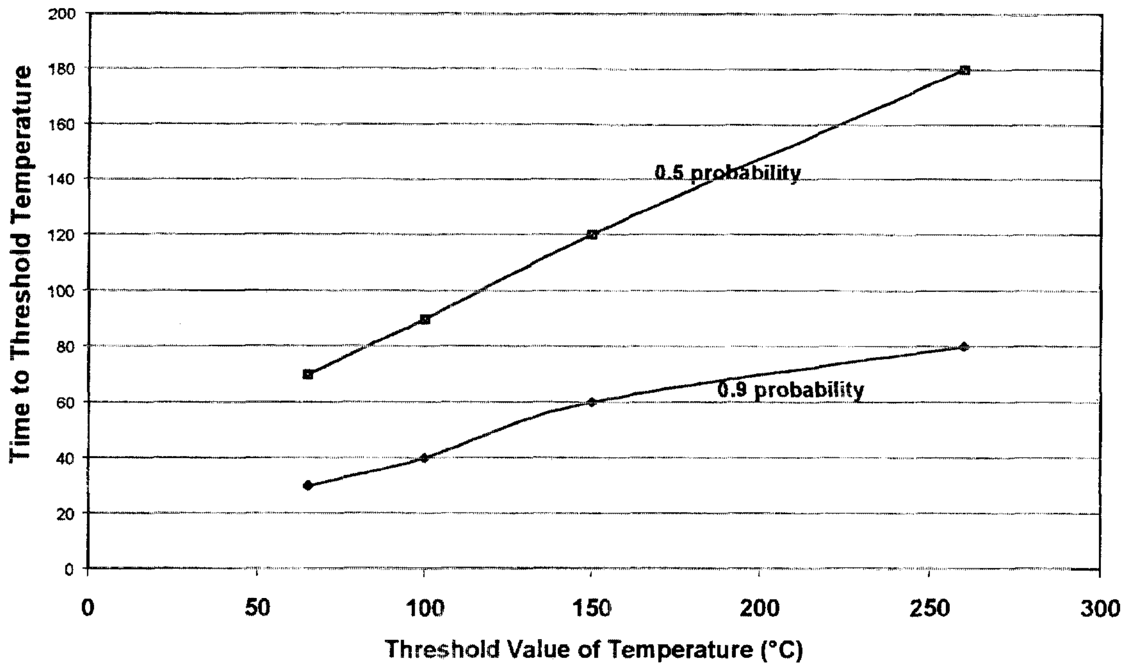

Figure 5.4 Time to Threshold Value of Upper Layer Temperature

Efforts to standardize performance criteria should be focused on which measures of performance are most meaningful not on the threshold level of temperature. Figure 5-4 shows a plot of threshold value for temperature in °C vs. time to threshold temperature at the 0.5 and 0.9 probability levels. Figure 5-4 provides a demonstration of the type of information that can be obtained from this type of analysis.

Design engineers sometime use a time element in the specification of performance criteria. The CDFs in Figure 5-5 show the time to reach 150°C as a threshold value and the time to reach and maintain at least 150°C for 5 minutes. However, one must be careful when using time elements in tenability criteria. A scientific study may show that a person can withstand a

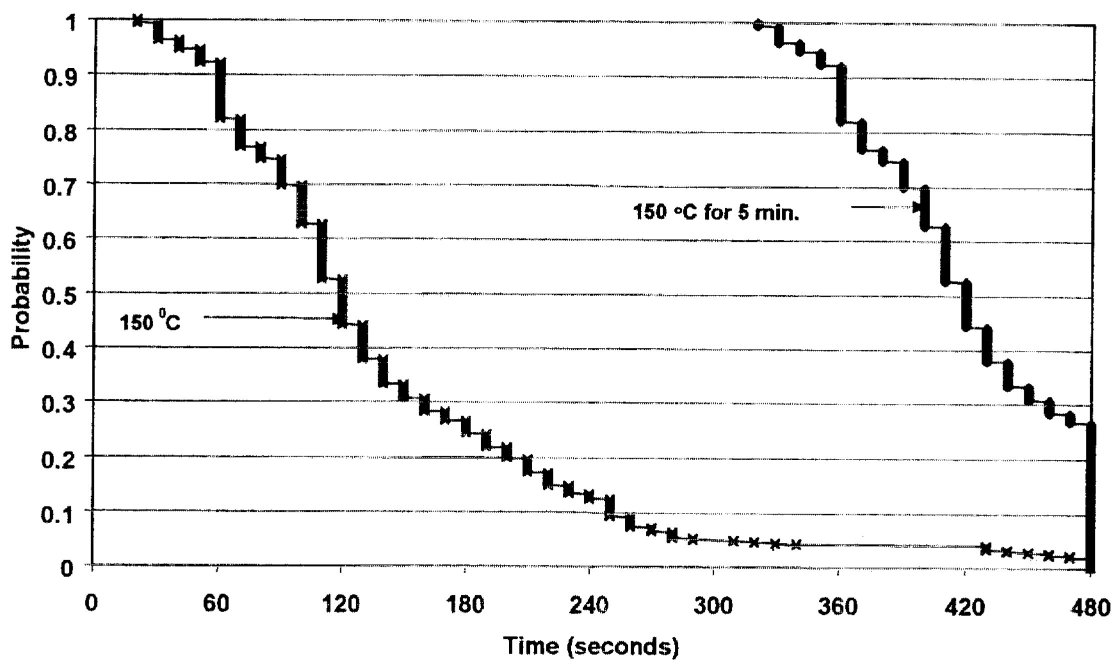

Figure 5-5. Time to Untenable Temperature

temperature of 120°C for 12 minutes. However, in a fire, the temperature is not constant but rather rises exponentially with time. In this case, counting from when the temperature first reaches 150°C to the end of the five- minute interval, the temperature could have reached as high 1000°C or more.

This evaluation only looks at temperature. In a real fire, smoke and asphyxiant gases as well as temperature can also lead to untenability of a room or corridor. The evaluation of time to untenability based on single performance criterion other than temperature as well as the time to untenability based on selecting combinations of performance criteria is discussed in Section 5.2.

The CDF's in Figures 5.1 - 5.5 are based on the minimum time to the threshold value anywhere in the apartment, which for temperature is always the room of origin. These CDF's provide time to egress safely from the room of origin. In order to set policies on calculating safe egress, one would like to know how sensitive time to untenability is as a function of different rooms in the apartment. Times to untenability elsewhere in the apartment outside the room of origin are expected to be longer.

One location central to most egress paths is the entranceway, the only door leading to the outside of the apartment. Figure 5.6 shows the CDF for time to untenability in the entranceway compared to the CDF for time to untenability in the room of origin.

Figure 5-6 shows that there is a 0.9 probability that the room of origin will remain at or below 100°C for 40 seconds or more. Figure 5-6. also shows that the entranceway will remain at or below 100°C for double that time or roughly 80 seconds or more. There is less difference between the time to untenability at the

100% level because 10% of the fires originate in the entranceway. Seventeen percent of fire scenarios never reach 100°C in the entranceway. These are shown by the solid vertical line in Figure 5.6 at an x-axis value of 480 seconds. Given that 10% of the fire scenarios start in the hall and an additional 17% that never reach untenability, 72% of the fire scenarios that start in a room other than the entranceway and make the entranceway untenable.

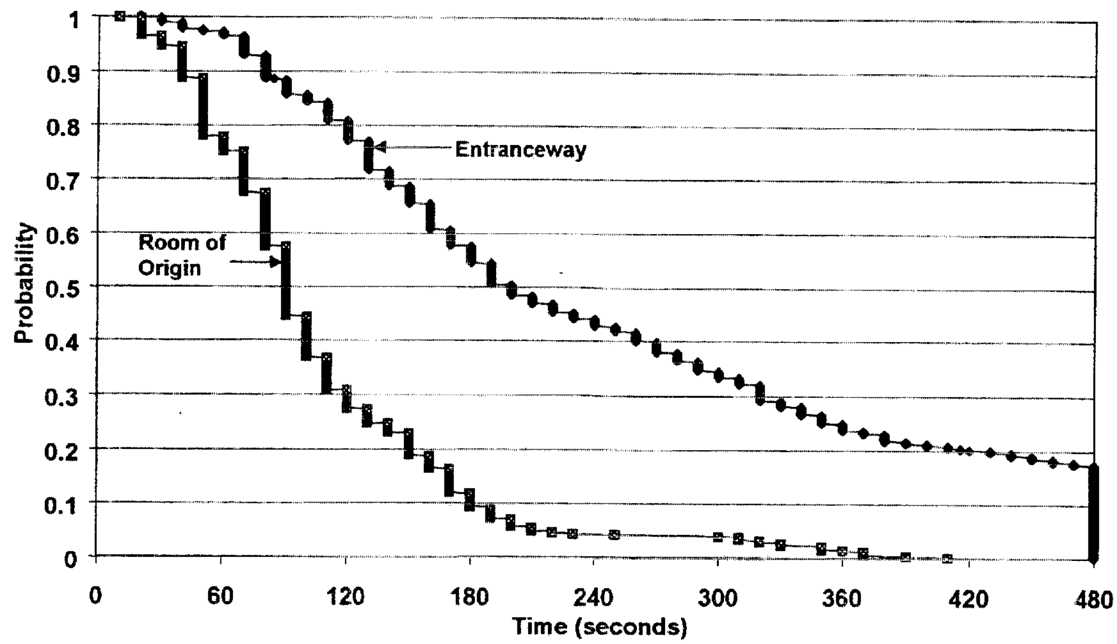

Figure 5-6. Time to 100°C Room of Origin vs. Entranceway

Given that time to untenability in the entranceway and time to untenability in the room of origin differs by at least a factor of two, an egress analysis that evaluates conditions in each room along the path of egress is warranted. Section 5.3.2 address egress analysis.

5.2 *Step 7e.* Effect of Performance Criteria Selected

In Section 4.3, we discussed several criteria for determining time to untenability. This section presents cumulative distribution functions and measures of sensitivity of the time available for safe egress based on each of these criterion.

5.2.1 Layer height

A performance criterion useful in design calculations is the height of the upper layer. Reduction in visibility as well as exposure to fire effluent gases and elevated temperatures occurs when the hot upper layer descends to the head height of the occupants. A person can lessen exposure for some time by keeping his/her head out of the hot upper layer, by crawling along the floor during egress. Figure 5-7 shows the time to decent of the upper layer to a height of 1.6 m above the floor and a height of 0.91 m above the floor. These heights correspond roughly to the average height of an adult standing or walking along a path of egress and to a level above the ground that allows for crawling underneath the layer.

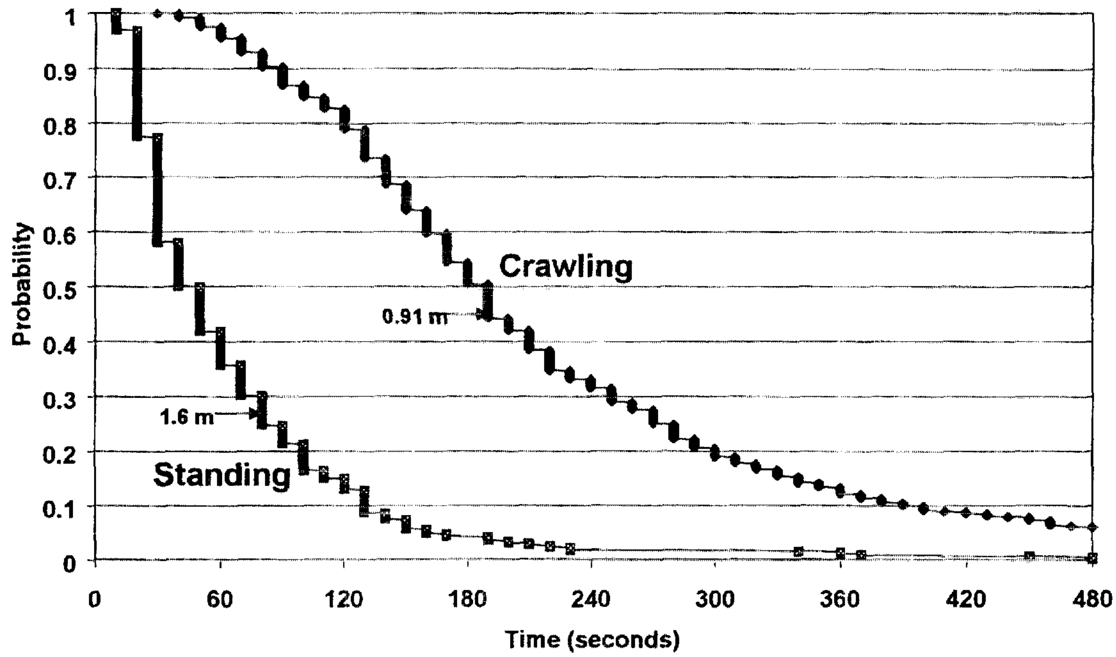

Figure 5-7. Time to Layer Decent

The CDF's in Figure 5-7 show a 0.9 probability of having 20 seconds or more until the layer reaches head height and 80 seconds or more before it reaches 0.91m above the floor. Correspondingly, there is a 0.5 probability of having 40 seconds or more before the layer reaches head height and 190 s or more before it reaches 0.91m above the floor. Thus, time to untenability is sensitive to layer height, showing a factor of three to five difference. Therefore, there is value in public education relating to staying low during egress.

5.2.2 Visibility

Figure 5-8 shows the time to an optical density of 0.2/m and the time to an optical density of 0.5 /m. Both the cumulative distribution function for time to 0.2/m and the cumulative distribution function for time to 0.5/m show a 0.9 probability of having 10 seconds or more before these obscuration conditions are reached. Our simulations only record values every 10 seconds. Thus, this result can be interpreted as that there is a 0.9 probability that within the first 10 seconds of the fire, an obscuration of 0.2/m is reached and before that 10-second time interval is up, an obscuration of 0.5/m is reached.

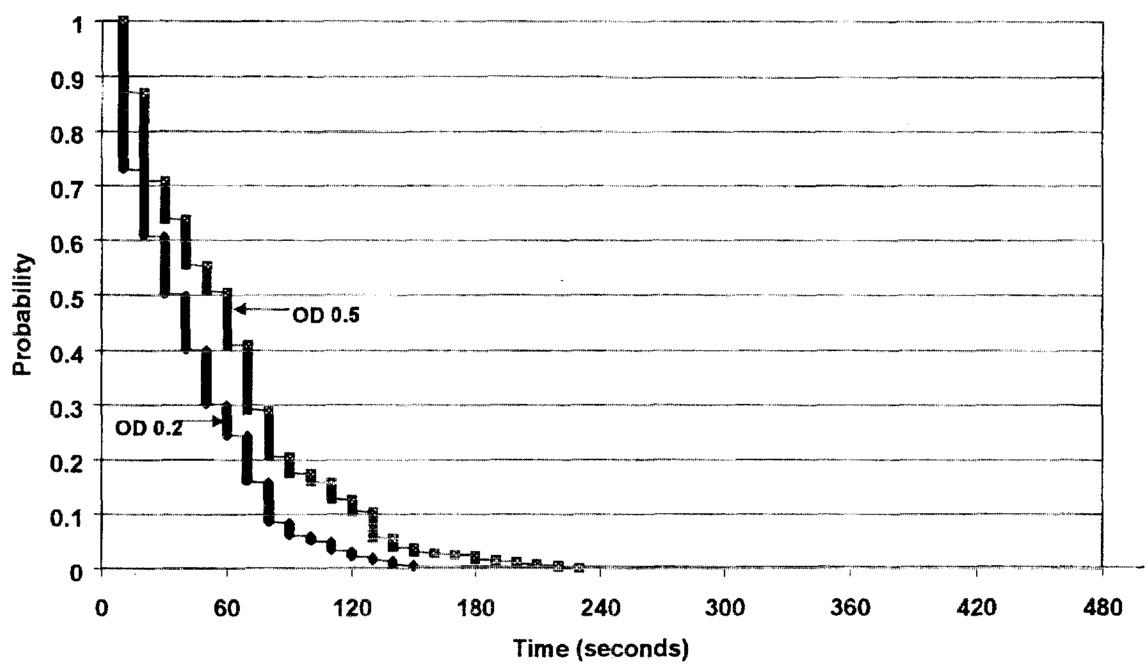

Figure 5-8. Time to Reduced Visibility

The cumulative distribution functions for optical density do not differ significantly. The results for this case study indicate that the difference between setting design criteria of 0.2/m and 0.5/m is not significant. Also, reduction in visibility is correlated with exposure to the upper layer.

5.2.3 Carbon Monoxide

Shown in Figure 5-9 are the cumulative distribution functions for threshold values of 1500 ppm and 3,000 ppm of carbon monoxide. If evaluating the first time tenability is exceeded anywhere in the apartment, the time to untenability due to temperature is always shorter than the time to untenability based on carbon monoxide alone, even at the most conservative threshold value for carbon monoxide. This is because the first time tenability is exceed is in the room of origin (where there is a fire). Outside the room of origin however, occupants may first encounter a build-up of asphyxiating gases.

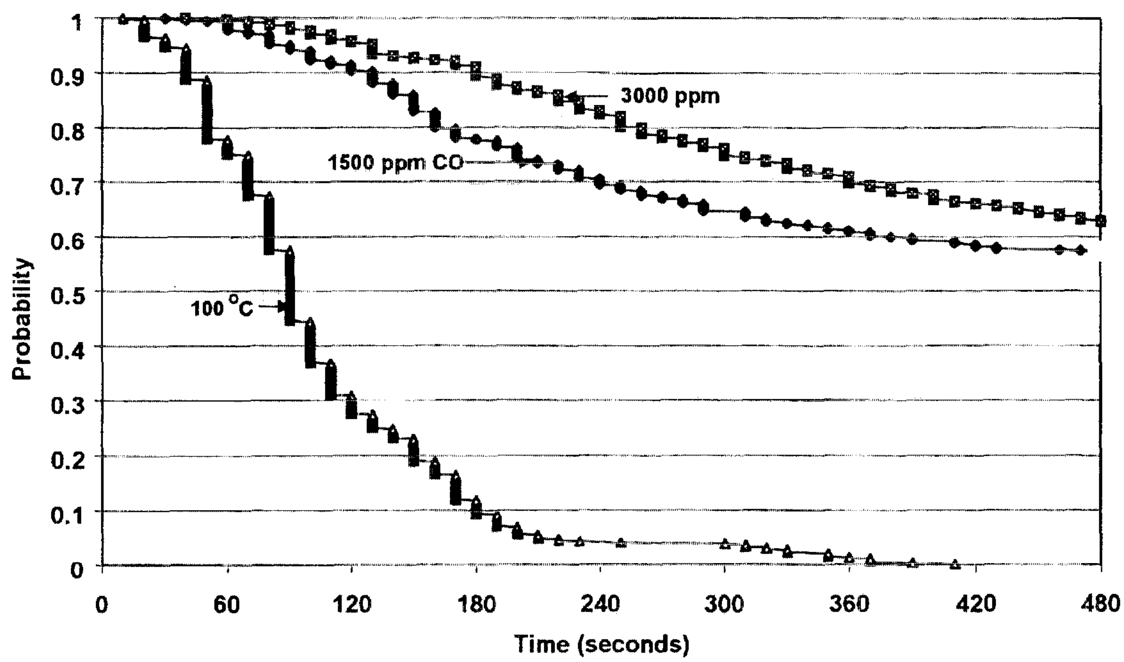

Figure 5-9. Time to Threshold Values of Carbon Monoxide

5.2.4 Oxygen deprivation

Figure 5-10 shows the cumulative distribution functions of time to threshold oxygen concentrations. Figure 5-10 shows that there exists a 0.9 probability of having 130 seconds or more until the oxygen concentration drops below 10% and a 0.9 probability of having 150 seconds before the oxygen concentration drops below 5.4%. For this case study, time to untenability is not very sensitive to these oxygen thresholds. Also, similar to carbon monoxide, oxygen alone is not likely to be the first tenability criterion to be exceeded in the apartment.

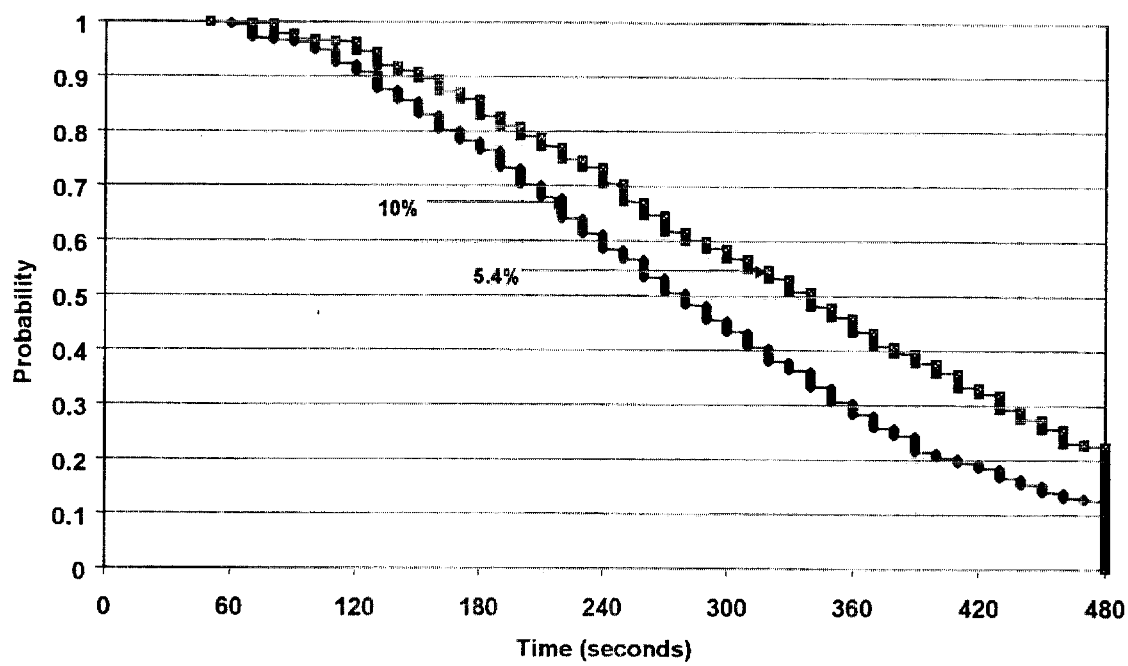

Figure 5-10. Time to Oxygen Threshold Value

5.2.5 Fractional Effective Dose/N-Gas Model

Figures 5-11 – 5-13 show the time to threshold values of fractional effective dose calculated using the Hazard equation (H-FED) and the Purser equations (P-FED) presented in Section 4.3.9. Figure 5-11 and 5-12 demonstrate that the difference between a 0.9 probability value for time to incapacitation and a 0.9 probability value for time to death are not very different. For the Hazard calculations, this difference is approximately 20 seconds and stays roughly constant across all probability levels.

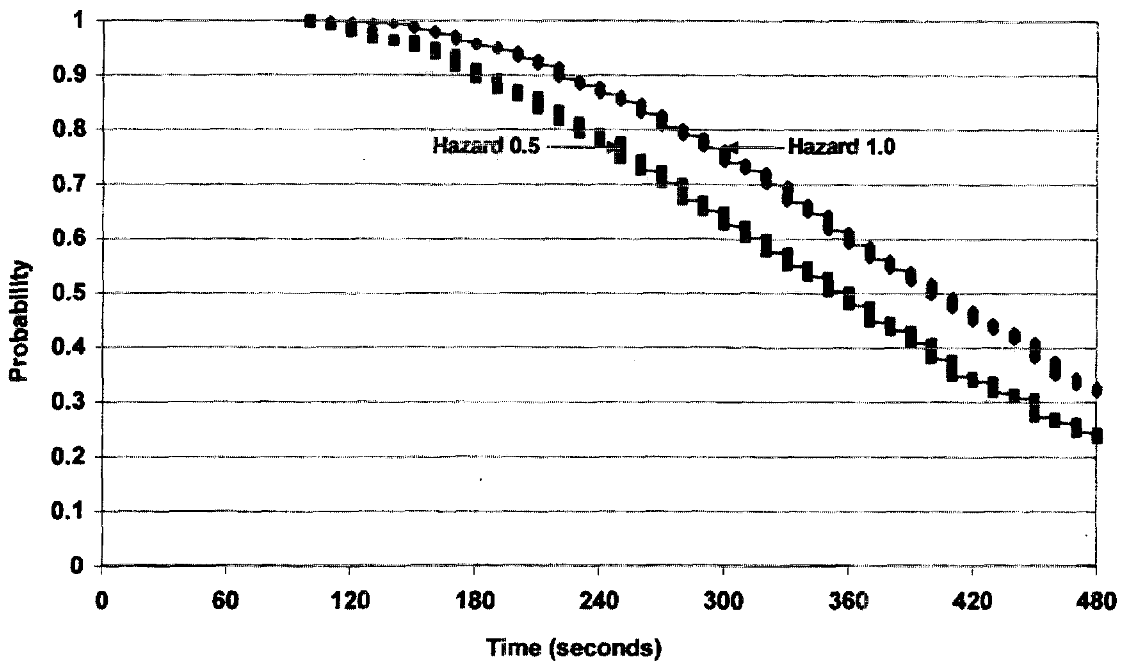

Figure 5-11. Comparison of Time to Incapacitation, Death- H-FED

The Purser equations give predictions that are also close together. At the 0.9 probability level, the difference in time to P-FED 1.0, incapacitation and P-FED of 2.0, death is also only 20 seconds. The cumulative distribution functions for time to incapacitation and death calculated from the Purser equations predict probabilities of times to untenability that are shorter than those predicted by the Hazard 1 equation. In fact, the CDF for time to incapacitation predicted by the Hazard 1 FED equation lies above the CDF for death predicted by the Purser

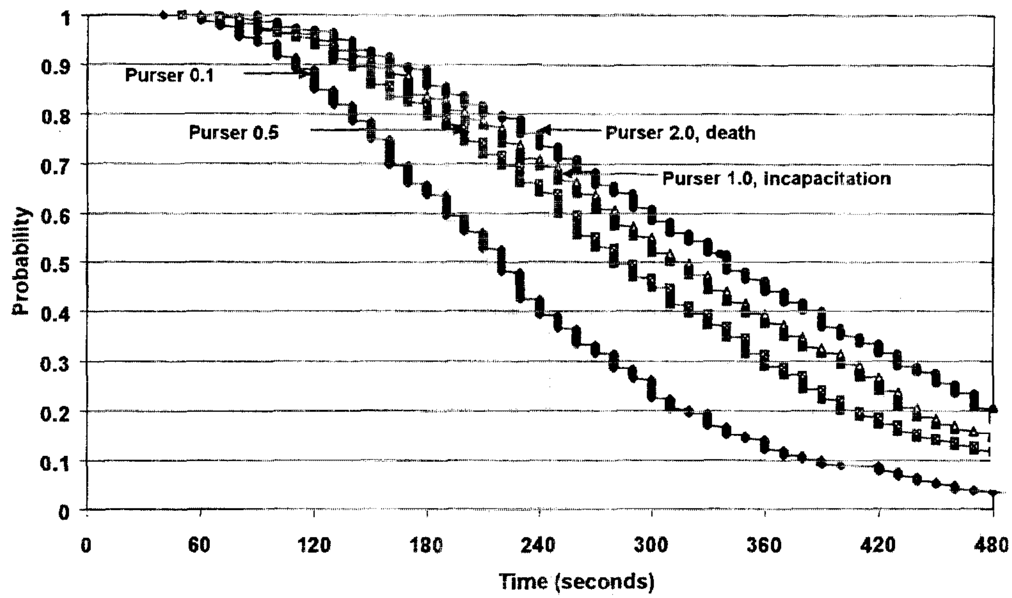

Figure 5.12 Comparison of Time to Various Levels of P-FED

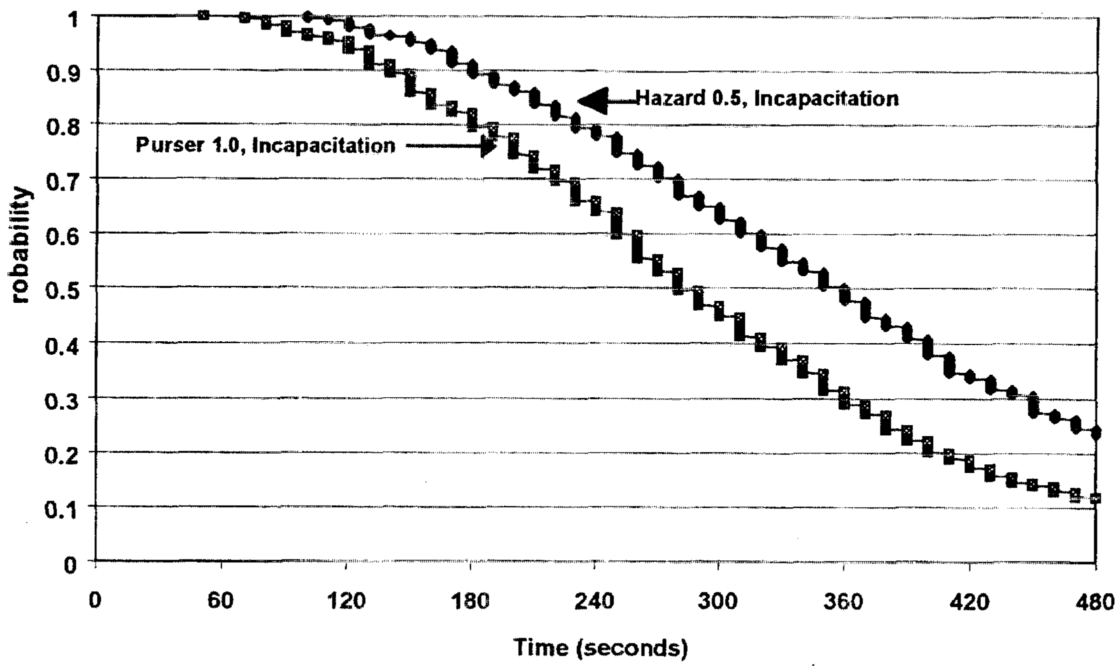

Figure 5-13. Comparison of Time to Incapacitation Levels of P-FED vs. H-FED

Figure 5-13 shows that there is a 0.9 probability of having 150 seconds or more and a 0.5 probability of having 310 seconds or more before untenability based on incapacitation is reached using the Purser FED equation. The Hazard 1 equations predict a 0.9 probability of having 180 seconds or more and a 0.5 probability of having 350 seconds or more before reaching incapacitation.

For predictions of lethality, the Purser equations predict a 0.9 probability of having 160 seconds or more and a 0.5 probability of having 340 seconds or more before lethal conditions are reached. The Hazard 1 equation predicts a 0.9

probability of having 220 seconds or more and a 0.5 probability of having 400 seconds or more before lethal conditions are reached.

It is also interesting to note the differences in prediction times for the 500 individual fire scenarios modeled. Figure 5-14 shows a histogram of the time to incapacitation predicted using the Hazard 1 FED equation and the time to incapacitation predicted using the Purser FED equation.

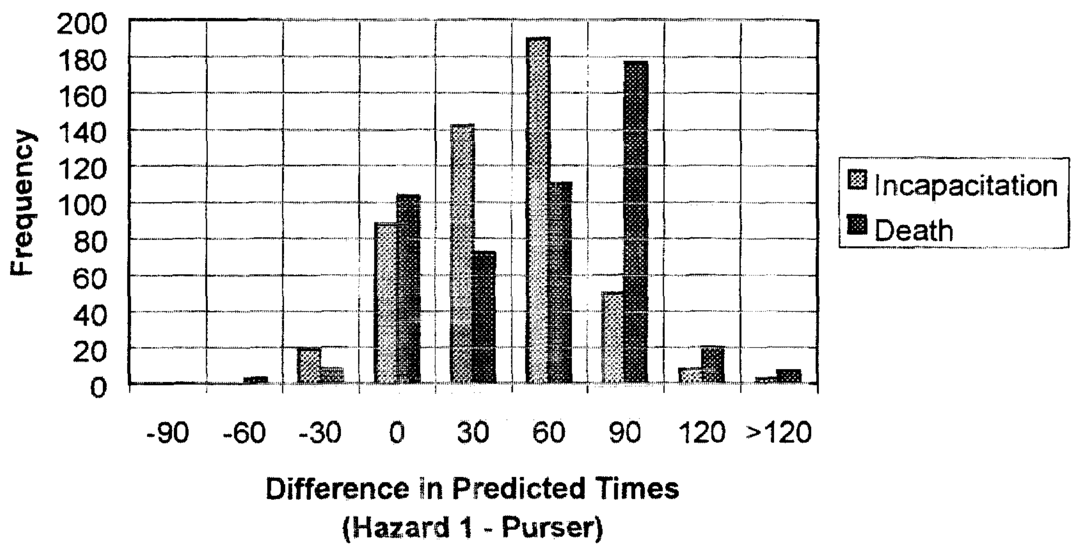

Figure 5-14. Histogram of Difference in Predicted Time to Incapacitation and Death (Hazard 1 - Purser)

Figure 5-14 shows that for calculations of time to incapacitation, 79% of the time Hazard 1 predicts a longer time to incapacitation than does the Purser equation. Fifty-four percent of the time, this difference is greater than ½ a minute, 22% of the time the difference is greater than one minute, and 1% of the time the difference in predicted times is greater than 2 minutes. For calculations of time to lethality, 77% of the time Hazard predicts a longer time to death than does the Purser equation. 65% of the time this difference is greater than ½ minute, 41% of the time it is greater than a minute, and 1% of the time it is greater than two minutes. Obviously, there is a need to standardize a method for calculating FED.

5.2.6 Flashover

Flashover is a phenomena which occurs when a number of interrelated criteria reach critical values. These include an upper layer temperature of around 600°C. Because flashover is marked by the instantaneous ignition of unburned fuel in the room, it serves as an upper bound for tenability. The cumulative distribution function for flashover is shown is Figure 5-15.

5.2.7 Selection of Final Design Criteria

At this step in the analysis, a probabilistic statement of performance is selected. A performance criterion, or set of criteria is selected along with a probability, a time, and a threshold value. Eventually, some or all of these elements should be mandated; however, more case studies of several performance criteria are needed before policy can be set intelligently. Figures 5-15 shows the criteria used to represent lethality, and Figure 5-16 shows the criteria used to represent incapacitation. Figure 5-16 also shows the time to layer decent and time to loss of visibility for comparison purposes.

Table 5-1. Probabilities of Time to Various Performance Criteria

Layer Height	1.0 (seconds)	0.9 (seconds)	0.7 (seconds)	0.5 (seconds)
LH 1.6 m	10	20	30	40
LH 0.91 m	30	90	140	190
0.2 OD/m	10	10	20	30
0.5 OD/m	10	10	30	60
1500 ppm CO	30	120	240	Not achieved
3000 ppm CO	40	180	360	Not achieved
<10% O_2	50	130	210	280
< 5.4% O_2	50	150	250	340
P-FED 1.0	60	150	240	310
P-FED 2.0	90	170	260	340
65 ^{0}C	10	30	50	70
100 ^{0}C	10	40	70	90
Flashover	70	90	330	470

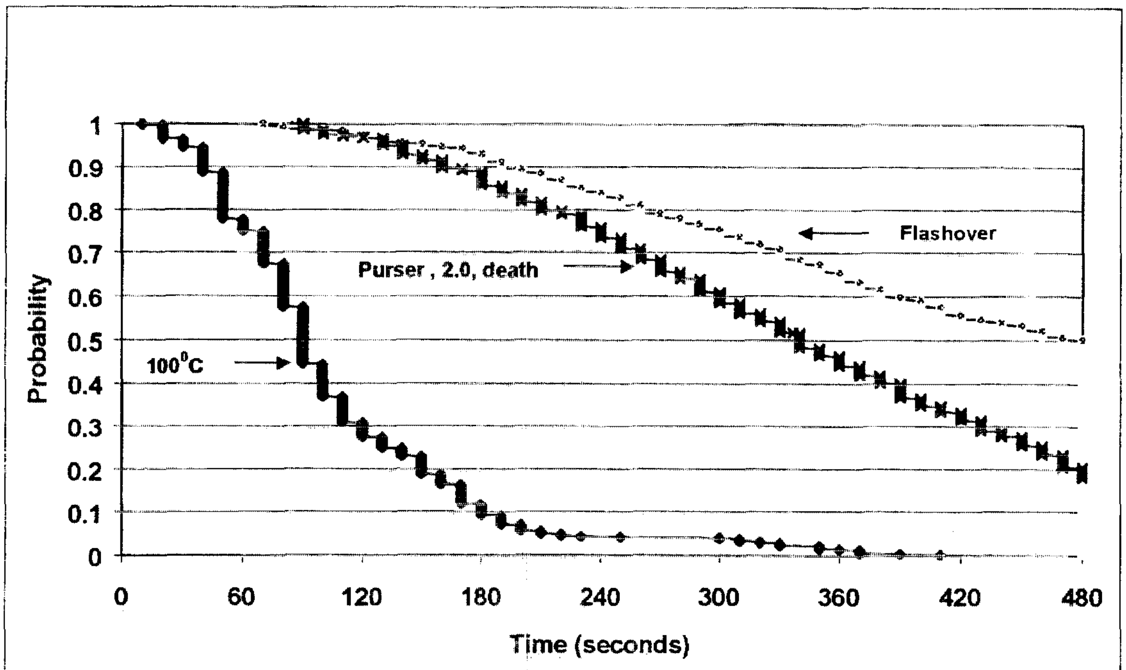

Figure 5-15. Criteria for Death and Flashover

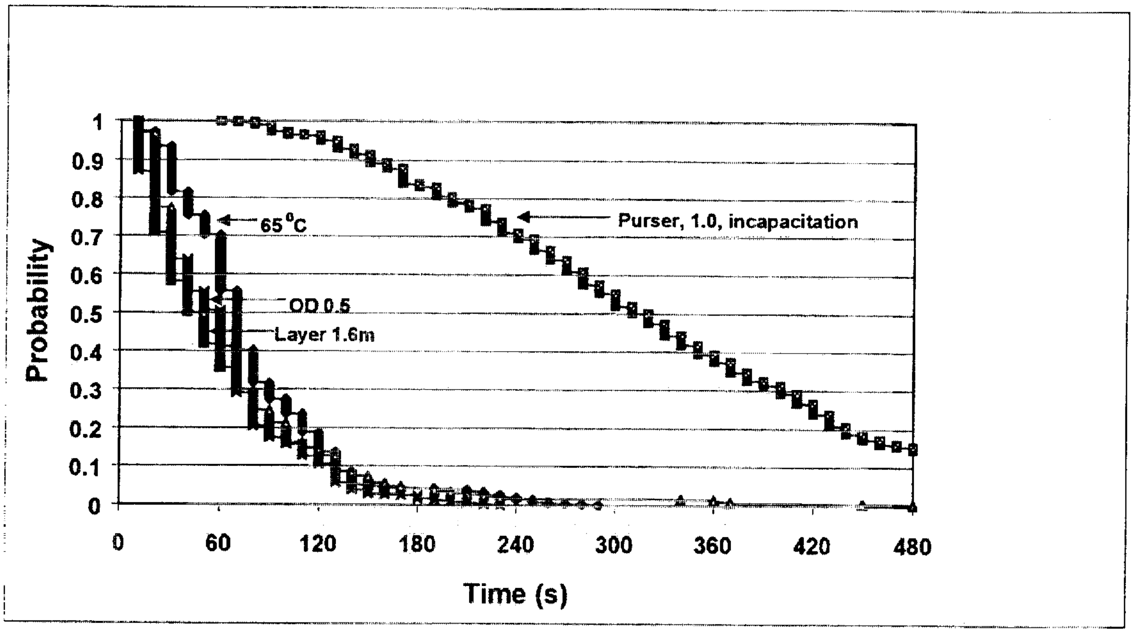

Figure 5-16. Criteria for Incapacitation and Visibility

For this analysis we will use a 0.9 probability of having 60 seconds or more of time to untenability (safe egress time) based on the minimum time to 0.5 P-FED OR 65°C.

5.3 *Step 7f.* Evaluation of the Base Case

5.3.1. Methods of Evaluation

It is often stated and easily agreed-upon that the time available for safe egress (time to untenability) must be greater than the time needed to evacuate the building safely. However, there are two very different ways one might apply this principle: a room of origin analysis and an egress path analysis. These are defined as follows:

Min, min or room of origin analysis: The time to untenability anywhere in the apartment including in the room of origin of the fire must be greater than the time needed for safe egress.

Egress path analysis: The time to untenability along the path of egress must be greater than the time needed for safe egress. Note that in an egress path analysis, tenability may be violated at one or more locations in the apartment, such as the room of origin of the fire.

Very different results may be obtained from an analysis based on min.min/room of origin than from an egress path analysis. Both types of analysis are presented for the case study to demonstrate each technique as well as to show that different design decisions would follow from each type of analysis. A summary of the percent of design fire scenarios that reached several thresholds for untenability by room is first presented. This data summarizes results for the base case design option, no sprinklers.

5.3.2 Summary of the Runs

When evaluating the ability of occupants to egress from the apartment safely, we must consider the conditions they will encounter inside and outside the room of origin. Table 5-2. summarizes the results of the five-hundred simulations in terms of the criterion of interest, the percent of scenarios that reach the tenability limits for that criterion (anywhere in the apartment or corridor), the range of times to reach the tenability value and the average and median values of time to tenability value.

Table. 5-2. Summary of Time to Untenability by Criteria

Criteria	% scenarios	Range of times	Average	Median
Visibility	100	10s to 230s	60s	60s
Layer height	100	10s to 450s	64s	40s
Incapacitation-temp (65C)	100	10s to 290s	77s	70s
Incapacitation – gases (P-FED 0.5)	88	50s to 470s	300s	280s
Death – temp	100	10s to 410s	106s	90s
Death (P-FED 1.0)	86	60s to 470s	290s	300s
Flashover	50	70S to 470s	290s	300s

The timeline of the median values shows that the layer descends to head level around 40 seconds in the room of origin. Shortly after, visibility drops to an unacceptable level. At 70 seconds, incapacitation due to temperature is reached, and at 90 seconds lethality due to temperature is reached. Incapacitation due to gases is reached around 280 seconds, this room reaches flashover over at 300 seconds, and lethality due to gases is reached around 315 seconds.

Table 5-2 shows that for the scenarios evaluated, visibility, layer height, incapacitation due to temperature, and death due to temperature are always reached somewhere in the apartment (100% of the scenarios). Concentrations of toxic gases at levels high enough to cause incapacitation and even death are reached over 85% of the time. For each criterion, the range of times to reach the design levels is quite wide. For example, the range of times to incapacitation due to temperature is from 10 seconds to 290 seconds. The range of times to reach incapacitation due to gases is between 50 seconds and 470 seconds for 88% of the five hundred scenarios that reach an incapacitating level of toxic gases somewhere in the apartment. The other 12% never reach this level. Two hundred and forty-six of the five hundred fire scenarios caused one or more rooms to reach flashover (based on an upper layer temperature of 600°C) in the eight minutes of simulation time for the fires.

Figure 5-17 shows the percent of fire scenarios that reached each of the tenability criterion in a given room. It can be seen that visibility is lost in approximately 90% or more of the scenarios in all rooms, including the corridor. Incapacitating temperatures are reached for over 50% of the scenarios in all rooms and over 90% of the time in the entranceway. Toxic gas concentrations high enough to cause incapacitation are reached only 32% of the time in the corridor but up to 66% of the time in the entranceway. Temperatures high enough to cause incapacitation are reached 52% of the time in the corridor and between 67% - 73% of the time in the kitchen, balcony, and bedroom. Incapacitating temperatures are reached around 85% of the time in the bathroom and living room, and 92% of the time in the entranceway.

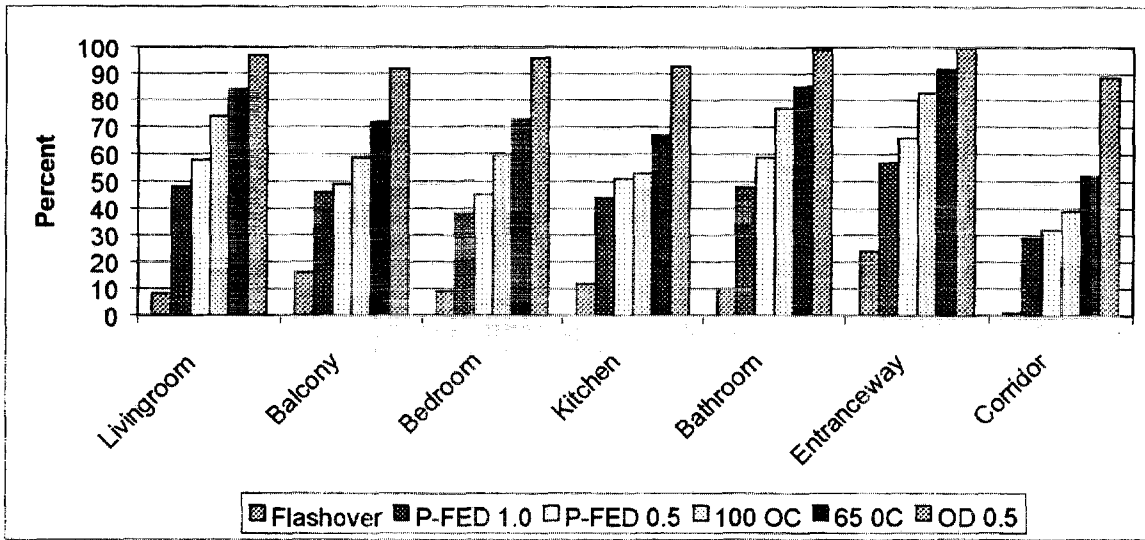

Figure 5-17. Percent of Cases to Reach Tenability Criteria in Each Room Within 480 Seconds

Temperatures and gas concentrations high enough to cause death occur most often in the entranceway. The corridor reaches tenability values high enough to cause death 29% - 39% of the time. The door between the corridor and the entranceway is open in 30% of the scenarios, and half-open in an additional 35% of the scenarios. Flashover occurs most often in the entranceway. This is most-likely due to the fact that there are several doors from the entranceway to other rooms in the apartment as well as a door to the corridor. Therefore, it is more likely that a fire in the entranceway will be supplied the oxygen needed for flashover.

The remainder of the analysis is based on incapacitation levels of temperature and toxic gas combinations. For each room, a certain percentage of fire scenarios never reach incapacitating levels of temperature or incapacitating levels of toxic gases. This may be due to the material burning, the fire size, the ventilation conditions, the location of the room relative to the room of origin of the fire, or simply to the fact that these simulations were limited to eight minutes (480 seconds). Table 5-3. gives for each room the percentages of the 500 fire scenarios that never reach incapacitating levels of temperature or toxic gases. Most notable is the entranceway, which only remains below incapacitating levels of temperature and toxic gases concentrations in 8% of the fire scenarios, and the corridor, which remains below incapacitating levels for almost half of the 500 scenarios.

Table 5-3. Percent of Fire Scenarios that Never Reach Incapacitation by Room

Room #	Scenarios Never Untenable 65C/P-FED0.5
Livingroom	15 %
Balcony	28 %
Bedroom	26 %
Kitchen	32 %
Bathroom	15 %
Entranceway	8 %
Corridor	47 %

5.3.3 Min,min/Room of Origin Analysis

A room of origin analysis evaluates the time to the first occurrence of untenability anywhere in the apartment. In this case study, the conditions used to define untenability are a temperature of 65°C or a P-FED of 0.5. The minimum time to either of these thresholds is taken for each room, and then the minimum across all rooms is identified. Thus, this type of analysis may be termed a min,min analysis. When temperature is included in the tenability criteria, temperature in the room of origin is always reached first, thus the term, room of origin analysis.

Min,min/room of origin analyses based on the first occurrence of untenable conditions anywhere in the apartment (often the room of origin) was discussed in detail in Section 5.2. as a function of several performance criteria and threshold values. As a result of that analysis, a probabilistic statement of performance was established as "a 0.9 probability of having 60 seconds or more of safe egress time based on 0.5 P-FED OR 65°C". A CDF of the min, min/room of origin analysis is shown in Figure 5-18 for the base case design, with no use of sprinklers.

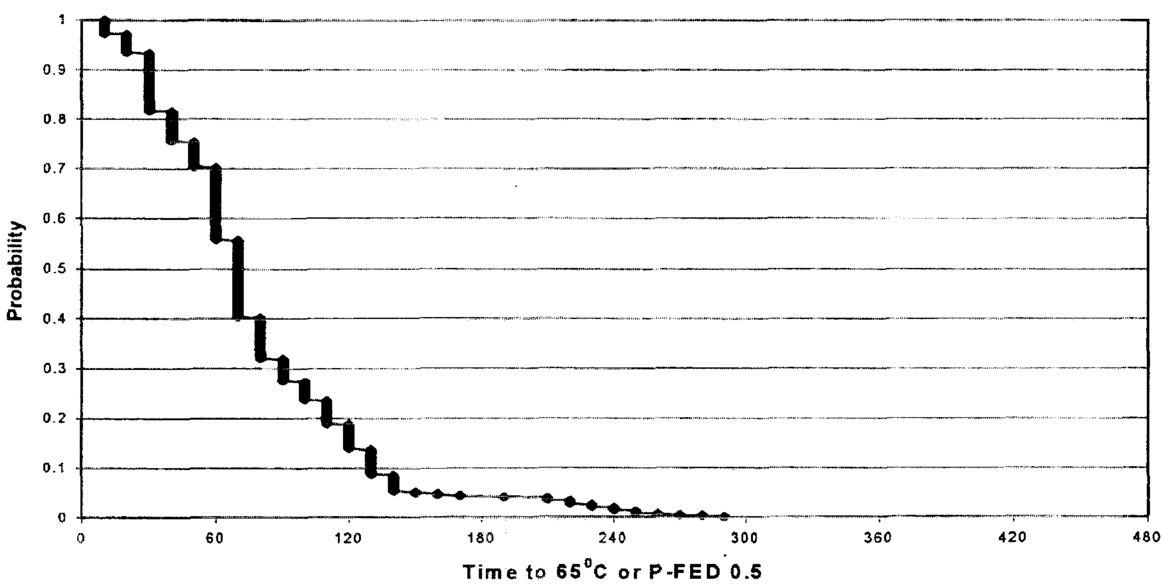

Figure 5-18. CDF of Time to Untenability, Min,min Analysis

It can be seen that for a min,min analysis, the base case design, no sprinklers is not sufficient to provide the stated 0.9 probability of having 60 seconds or more before untenable conditions are reached. The cumulative distribution function for time to the first occurrence of either 65°C or P-FED of 0.5 demonstrates that there is only a 0.7 probability of having 60 seconds or more before untenable conditions are reached.

5.3.4 Egress Path Analysis

Egress paths from anywhere in this apartment would lead through the entranceway and corridor. Egress from the kitchen and balcony would additionally lead though the living room. For occupant safety, each room along the path of egress must remain tenable for the time necessary to egress.

Table 5-4 summarizes the time to untenability in each of the rooms along the egress path, as a function of the room of origin of the fire. Table 5-4 provides the range of times resulting from the 500 design fire scenarios, the median of those times, and the 25% and 75% values. Values of time to the minimum of 65°C or a P-FED of 0.5 in the living room based on room of origin of the fire can be read from the CDFs in Figure 5-19.

It can be seen from table 5-4 that at the median values, the corridor remains tenable for the eight minutes of the simulation unless the fire starts in the corridor, entranceway, or bathroom. The median values for the entranceway show that it reaches untenability during the 8-minute simulation times regardless of where the fire starts. The living room becomes untenable for all rooms of origin except when the fire starts in the corridor.

Table 5.4 Time to Untenability along the Path of Egress as a Function of Room of Fire Origin

Range (Median) .25 .75	Time to Untenability Living/Dining Room (seconds)		Time to Untenability Entranceway (seconds)		Time to Untenability Corridor (seconds)	
ORIGIN	65 C	P-FED .5	65 C	P-FED .5	65 C	P-FED .5
Living room	20-190 (90) 80 100	130-500 (340) 275 400	60-400 (120) 100 160	160-500 (410) 325 500	200-500 (500) 400 500	290-500 (500) 500 500
Balcony	40-400 (140) 100 180	120-150 (390) 320 500	50-500 (210) 150 300	130-500 (500) 360 500	150-500 (500) 500 500	230-500 (500) 500 500
Bedroom	80-500 (310) 180 453	170 –500 (500) 430 500	30-500 (110) 90 150	110-500 (380) 290 485	140-500 (500) 465 500	200-500 (500) 500 500
Kitchen	40-500 (120) 80 150	110-500 (320) 220 380	50-500 (170) 120 280	120-500 (360) 270 500	120-500 (500) 168 430	230-500 (500) 500 500
Bathroom	90-150 (300) 220 413	280-500 (500) 495 500	40-220 (95) 78 130	150-500 (360) 250 435	50-500 (220) 168 430	180-500 (500) 378 500
Entranceway	60-500 (140) 110 230	160-500 (460) 360 500	10-140 (60) 30 70	50-500 (330) 210 410	110-500 (460) 280 500	260-500 (500) 450 500
Corridor	160-500 (500) 363 500	300-500 (500) 500 500	80 – 500 (300) 203 500	210-500 (500) 318 500	20-290 (130) 70 140	150-500 (380) 268 433

Note - 500=not reached within simulation time of 480 seconds (8 minutes)

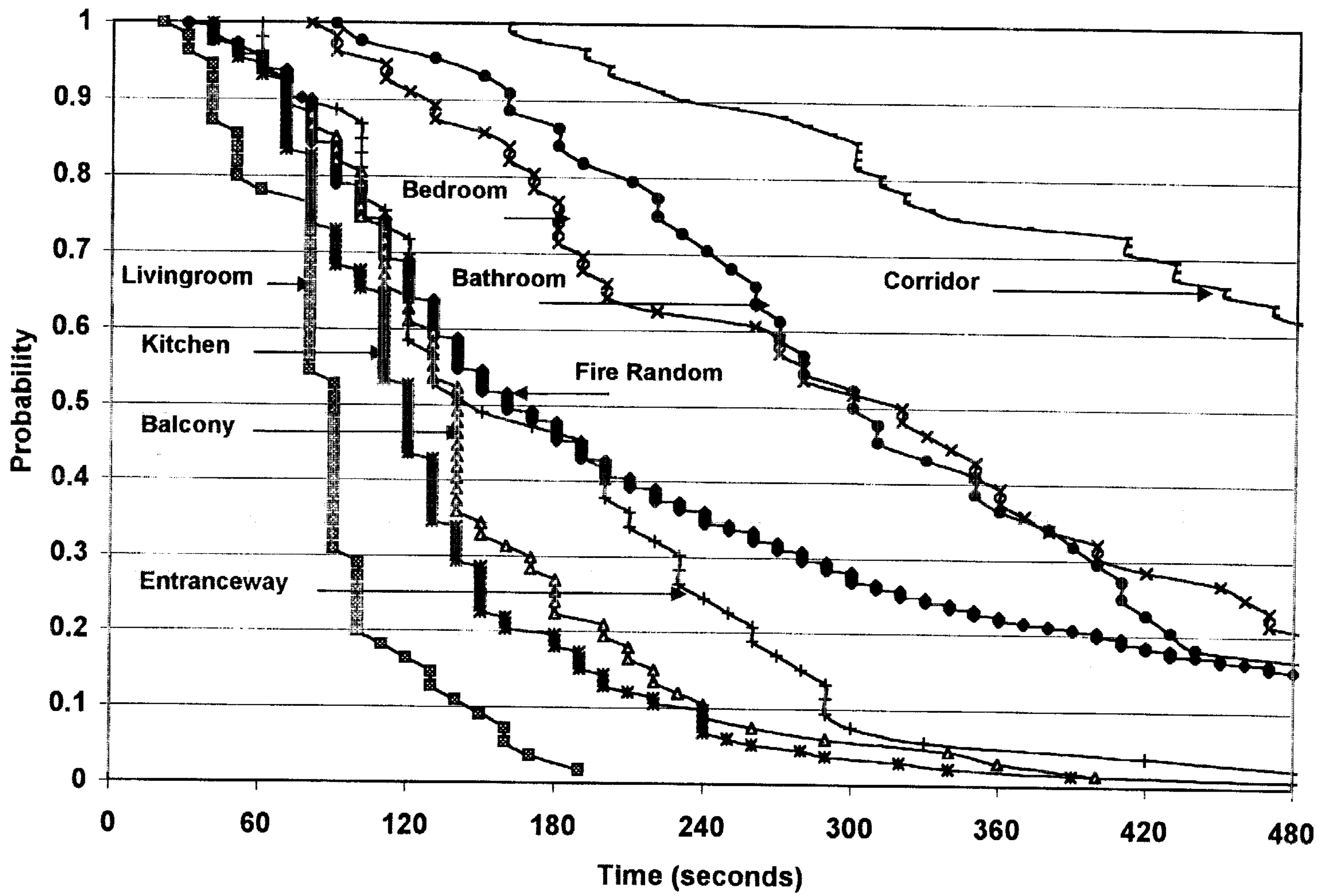

Figure 5-19. Time to Untenability (65 0C or P-FED 0.5) in the Livingroom by Room of Origin

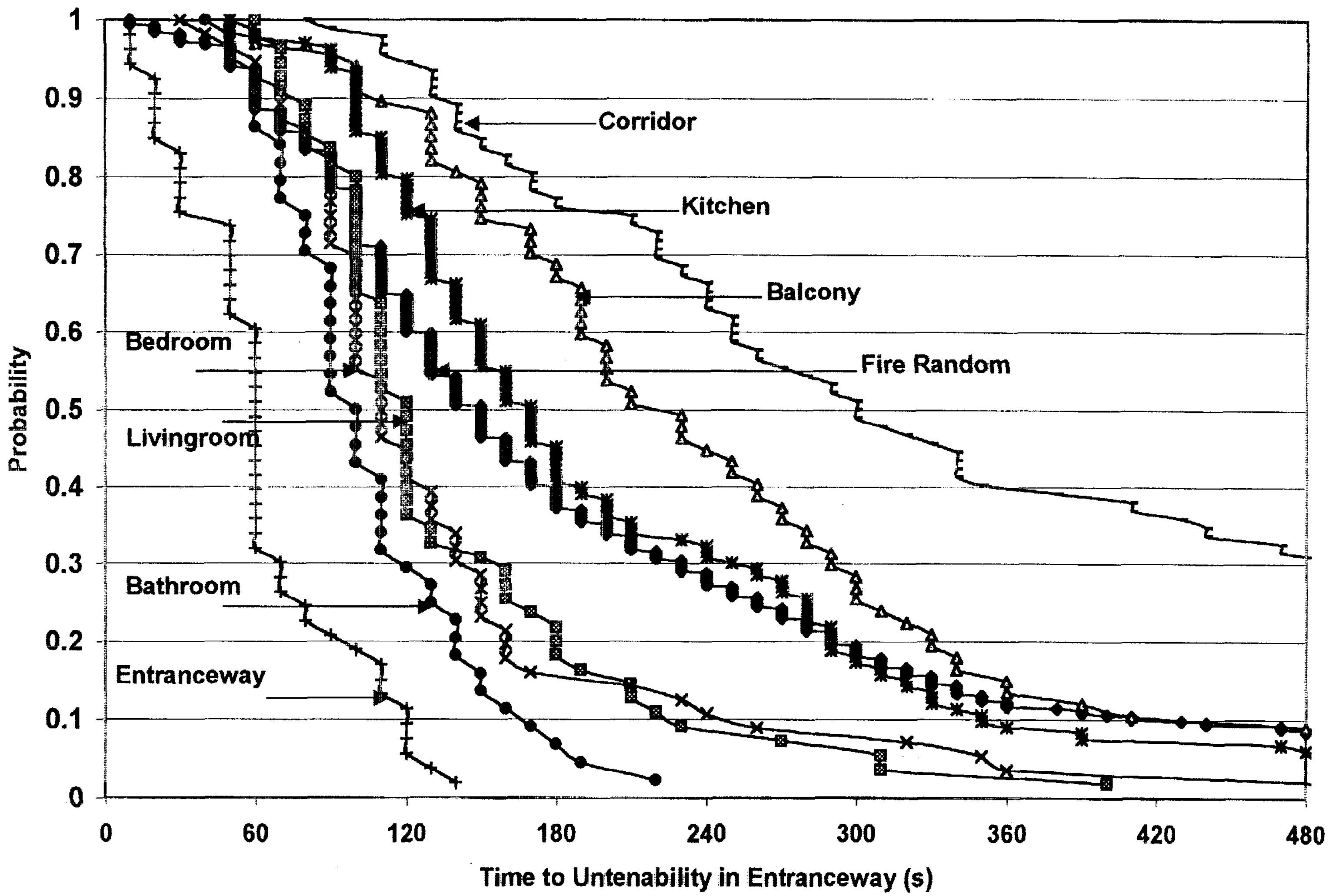

Figure 5-20. Time to Untenability (65 0C or P-FED 0.5) in the Entranceway by Room of Origin

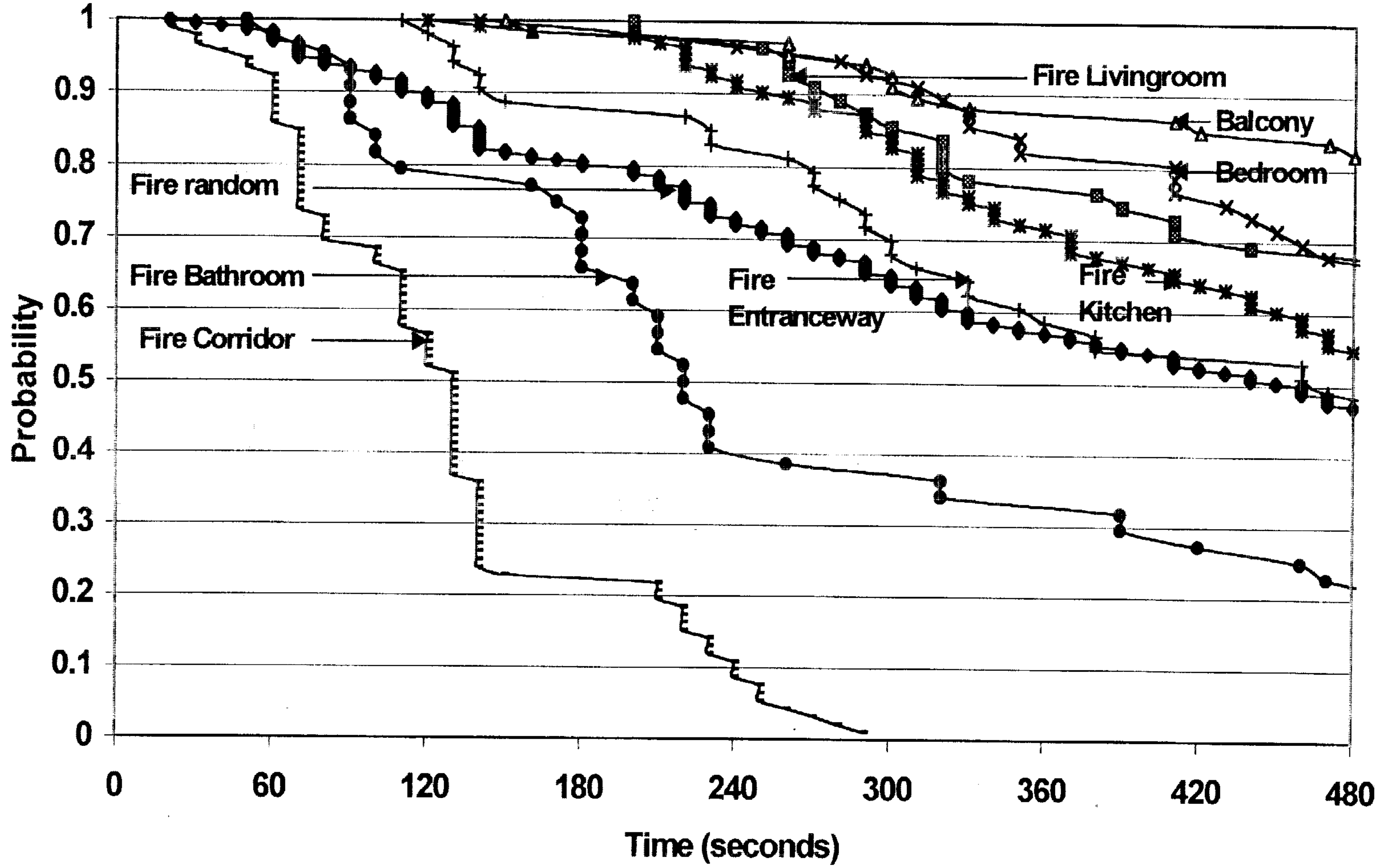

Figure 5-21. Time to Untenability (65 0C or P-FED 0.5) in the Corridor by Room of Origin

Figures 5-20 and 5-21 provide the same information for the entranceway and corridor respectively. These presentations are useful in establishing probabilistic statements of performance specific to rooms along the egress path.

Example paths of egress evaluated are from the balcony though the living room and entranceway to the corridor. The path from the balcony is interesting because it is the longest path out of the apartment and also because occupants originally in another room when may go to the balcony to look out or as an seemingly safe place to wait. The second path of egress evaluated is from the bedroom through the entranceway to the corridor. This path is intrestering because of the fact that occupants in the bedroom may be sleeping and thus experience a delay in their reaction times.

Figure 5-22 shows a plot of all five hundred fire scenarios. The x-coordinate of each point is the time to untenability on the balcony based on the minimum of 65°C or 0.5 P-FED. The y-coordinate for each point is the minimum time to untenability based on 65°C or 0.5 P-FED anywhere along the egress path, i.e., in the livingroom, entranceway, or corridor. For 89% of the scenarios, untenability is reached somewhere on the egress path before the balcony becomes untenable. This leads to a potential trapped situation in which by the time an occupant on the balcony begins to be affected by the smoke and heat the balcony is already untenable somewhere along his/her path of egress. For the bedroom, a similar

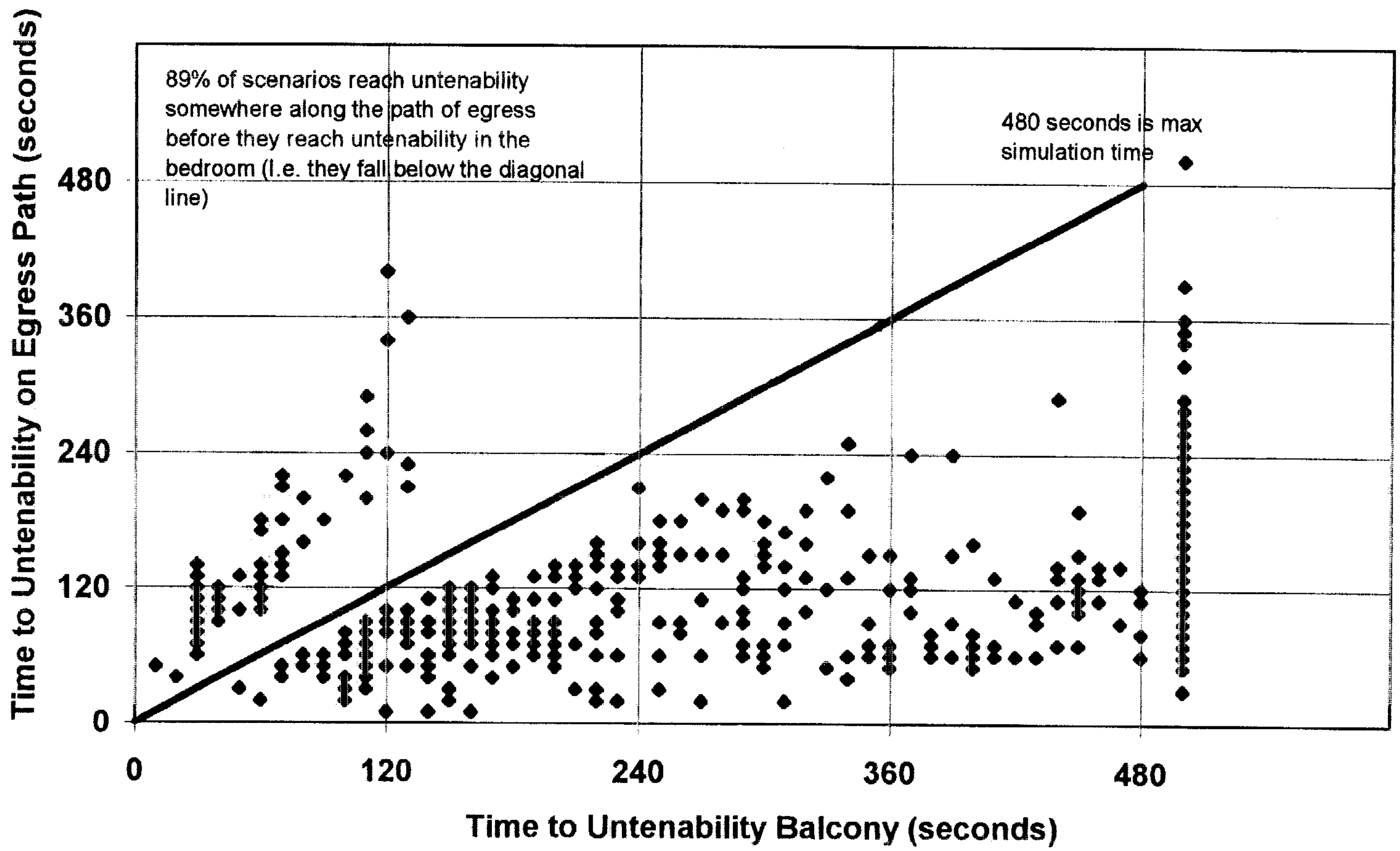

Figure 5-22. Potential Traps

analysis of potential traps was conducted using the same performance criteria, and 87% of the scenarios became untenable somewhere along the egress path before becoming untenable on the bedroom.

Figures 5-23 to 5-25 show the time to untenability in the bedroom or balcony graphed vs. time to untenability on the egress path. Figure 5-23 represents egress from the bedroom and shows that without automatic fire sprinklers, only 2.4% of the fire scenarios remain tenable in the bedroom and along the path of egress for the entire 8-minute simulation. In 89.8% of the scenarios, both the bedroom and conditions along the path of egress from the bedroom remain tenable for at least one minute, 48.6% of the scenarios remain tenable for at least 2 minutes; 16% of the 500 scenarios remain tenable for at least 4 minutes; and 4.0% of the scenarios remain tenable for at least 6 minutes.

Figure 5-24 shows the time to untenability in the bedroom vs. time to untenability on the egress path. Similar findings to those of the egress path from the bedroom are shown. In 84.2% of the fire scenarios, there is at least one minute of safe egress time on the balcony and along the egress path. For 30.2% of the scenarios, there are at least 120 seconds of safe egress time; for 4% of the scenarios there are at least 4 minutes; and for less than 1% of the scenarios is there greater than 6 minutes.

Figure 5-25 shows how the percent of fire scenarios providing at least one minute and up to 8 minutes of time to untenability on the balcony and along the path of egrss from the balcony changes if visibility is included as one of the tenability criteria. Comparing Figure 5-25 that includes obscuration to Figure 5-24 that does not, we see that the percent of fire scenarios providing at least a minute of safe egress time is 84.2% with out consideration of visibility and 62.8% with consideration of obscuration. Or, conversely, the number of scenarios less than a minute of safe egress time from the balcony rises from 15.8% to 32.2% with consideration of obscuration. We did not consider obscuration a tenability criteria here because of the familiarity of the occupants with their own apartments.

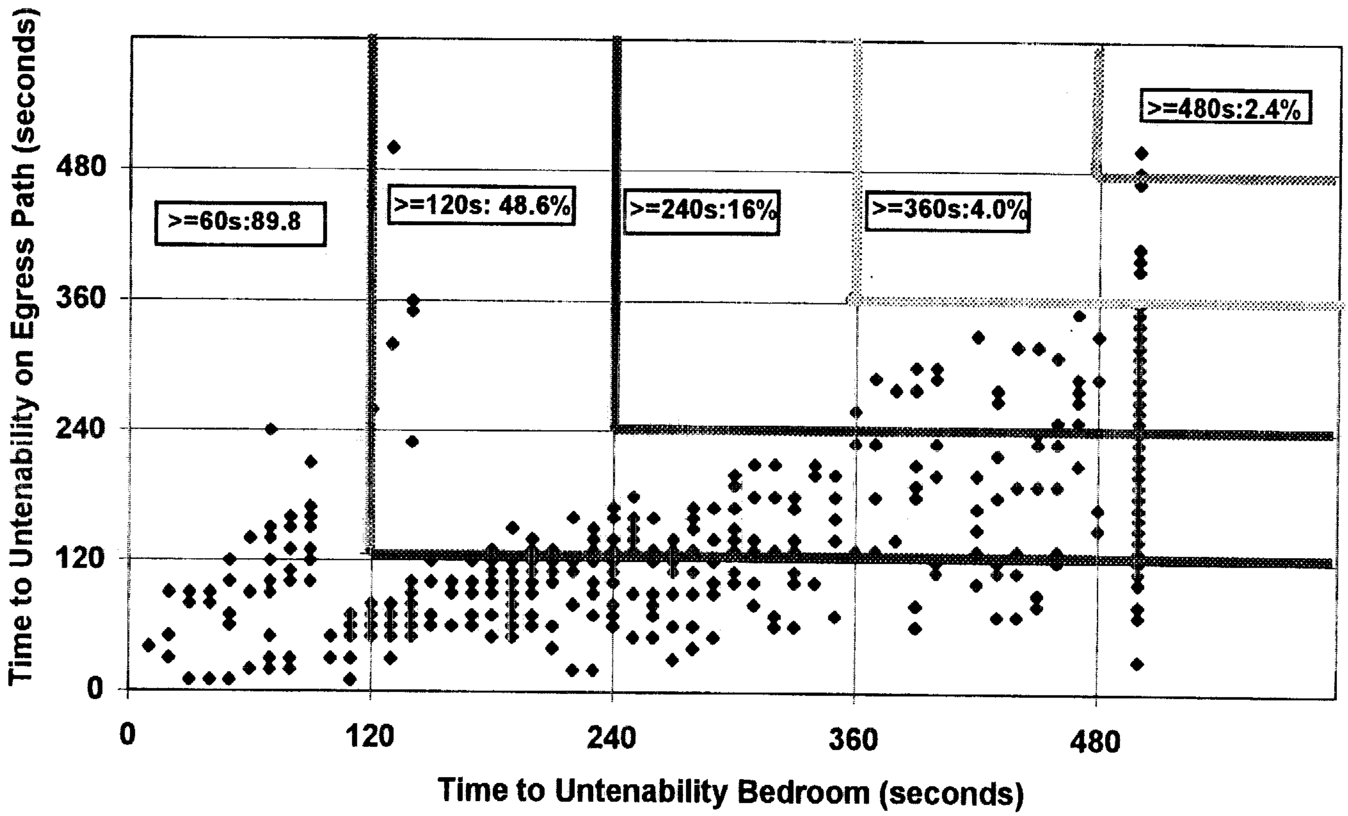

Figure 5-23. Time to Untenability (65 0C or 0.5 P-FED)Bedroom and Egress Path, No Sprinklers

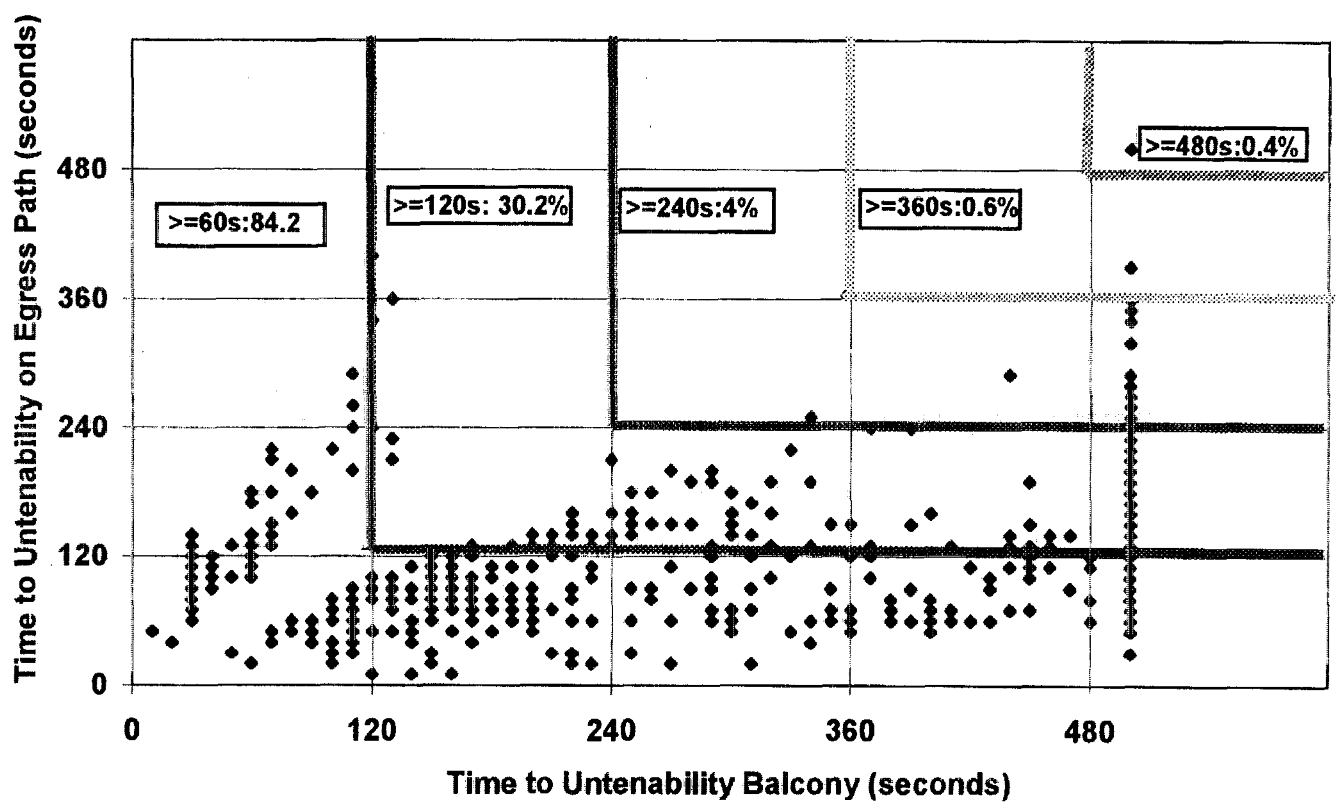

Figure 5-24. Time to Untenability (65 0C or 0.5 P-FED) Balcony and Egress Path, No Sprinklers

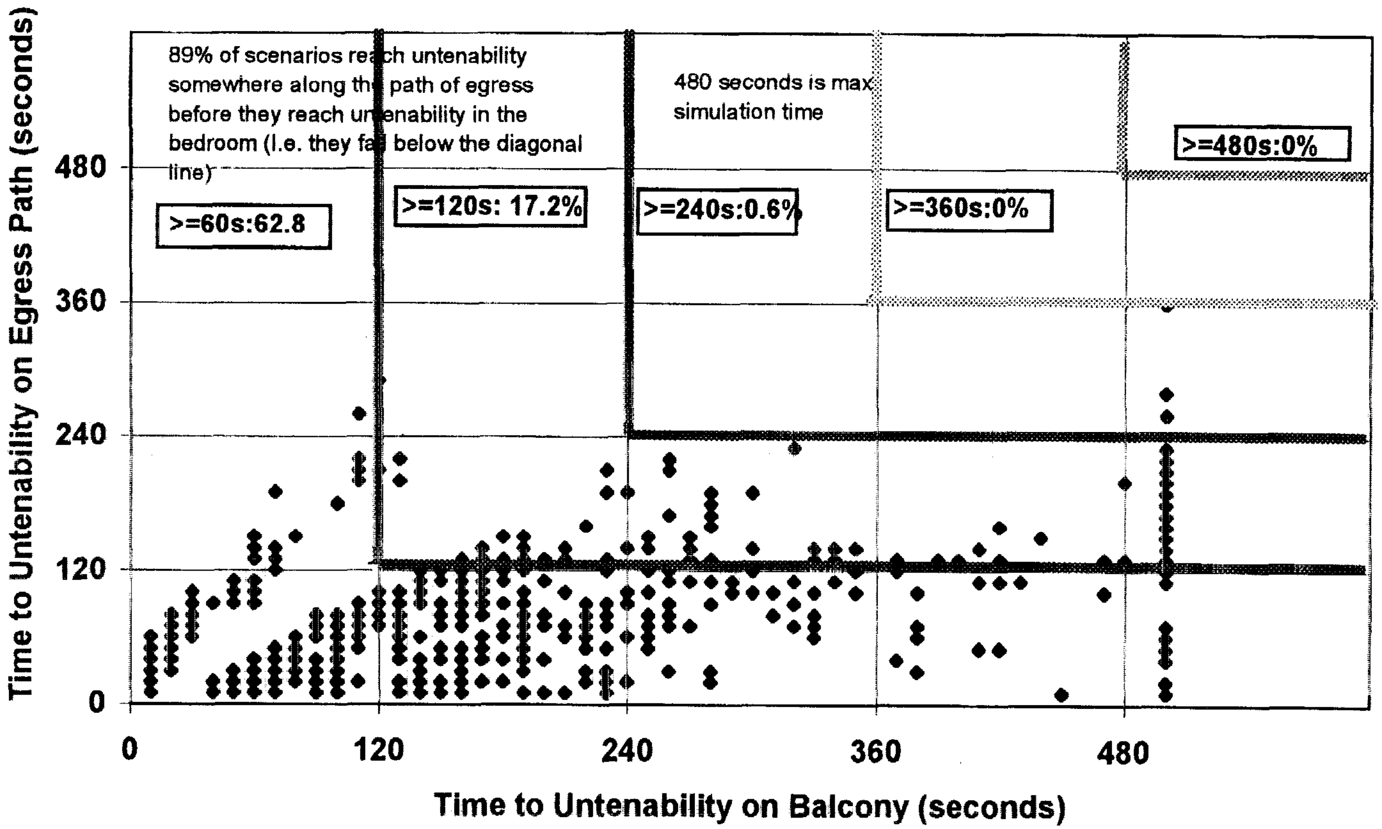

Figure 5-25. Time to Untenability (65 0C or 0.5 P-FED or 0.5 OD) Balcony and Egress Path, No Sprinklers

5.4 *Step 7g.* Determine Effect of Each Candidate Design on Each of the Scenarios

The analysis presented for Design 1, no fire sprinklers represents the base case design. Figure 5-24. shows this analysis. With no installed sprinklers, 89% of the scenarios become untenable somewhere along the path of egress before becoming untenable on the balcony. This leads to a potential trapped situation in which the occupant who may be on or go to the balcony has a false sense of the conditions developing in the living room, entranceway, or corridor. Also for this base case, 84.2% of the scenarios provide 60 seconds or more of time to untenability on the balcony as well as in all rooms along the path of egress. This means that 15.8% of the scenarios provide less than 60 seconds of safe egress time. For the base case of no sprinklers, less than 0.5% remain tenable for the 8 minutes of simulation time.

If automatic fire sprinklers are installed in the corridor only, the percent of scenarios that provide greater than 60 seconds of safe egress time goes up only slightly, from 84.2% to 85.6% as seen in Figure 5-26..The percent of fire scenarios becoming untenable somewhere along the egress path before becoming untenable on the balcony falls from 89% to 68%.

If automatic fire sprinklers are installed in the entranceway and corridor, the percent of fire scenarios that become untenable in less than one minute goes down to 9%. For 91% of the scenarios, the balcony and each room along the path of egress remain tenable (less than 65°C or 0.5 P-FED) for at least one minute. This can be seen in Figure 5-27.

Results of the percent of scenarios providing at least one, two, four, six, or more minutes are summarized in Table 5-5 for egress from the balcony.

Table 5-5. Time to Untenability/Safe Egress from Balcony

SAFE TIME ON BALCONY AND ON EGRESS PATH	NO SPRINKLERS	SPRINKLERS CORRIDOR	SPRINKLERS ENTRANCEWAY AND CORRIDOR
<60s	15.8%	14.4%	9.0%
>=60s	84.2%	85.6%	91.0%
>=120	30.2%	39.2%	61.0%
>=240s	4.0%	21.0%	43.4%
>=360	0.6%	19.0%	36.4%
>=480	0.4%	18.8%	32.8%
% possible traps	89.0%	67.8%	53.8%

However, it is unknown where each occupant will be when he/she is alerted of a fire condition. Also, because occupants may not commence egress immediately, a full egress analysis must account for the time available for safe egress from each of the rooms in the apartment and along the path of egress. The method of analysis demonstrated above for the path of egress from the balcony was

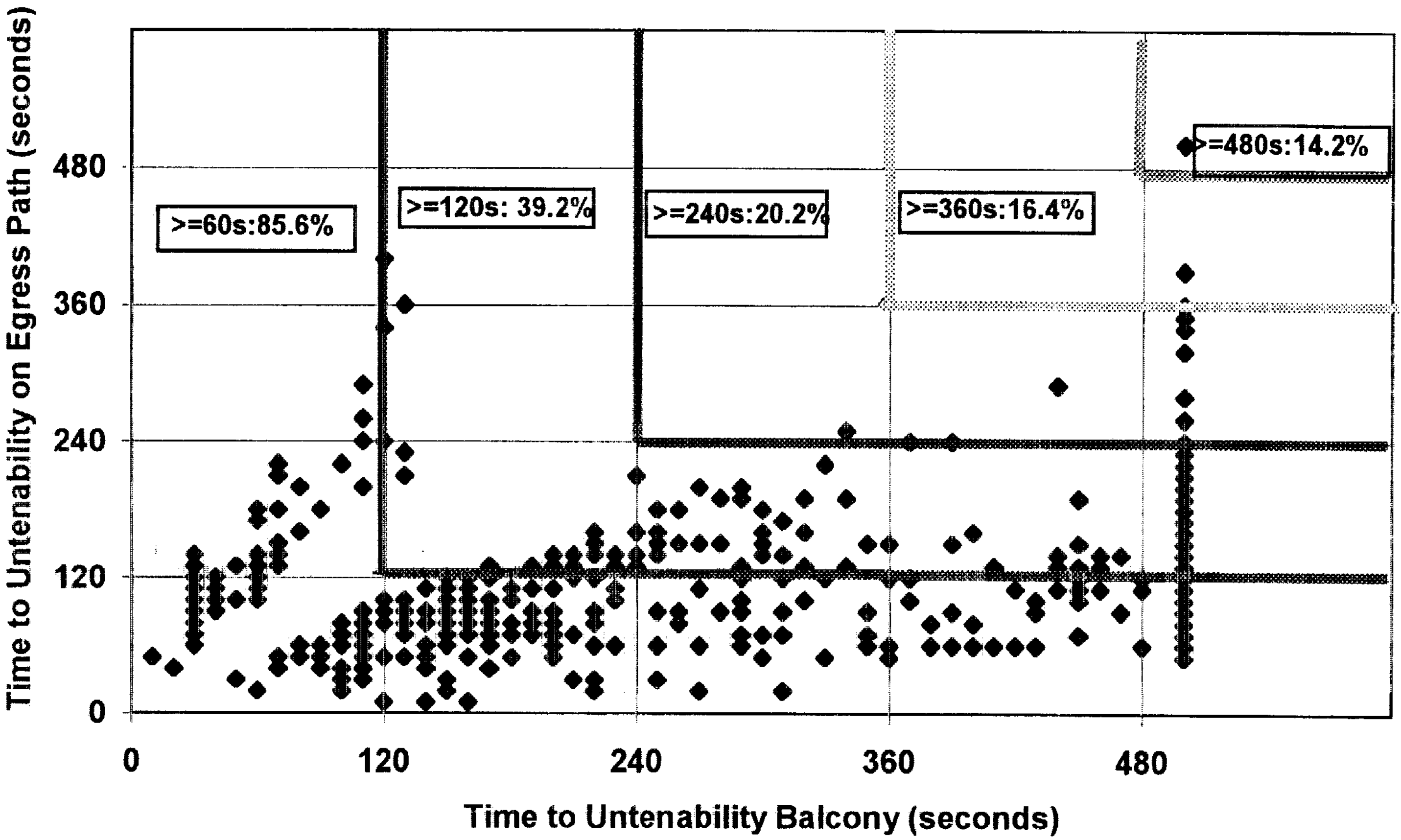

Figure 5-26. Time to Untenability (650C or 0.5 P-FED) Balcony and Egress Path, Sprinkler in Corridor Only

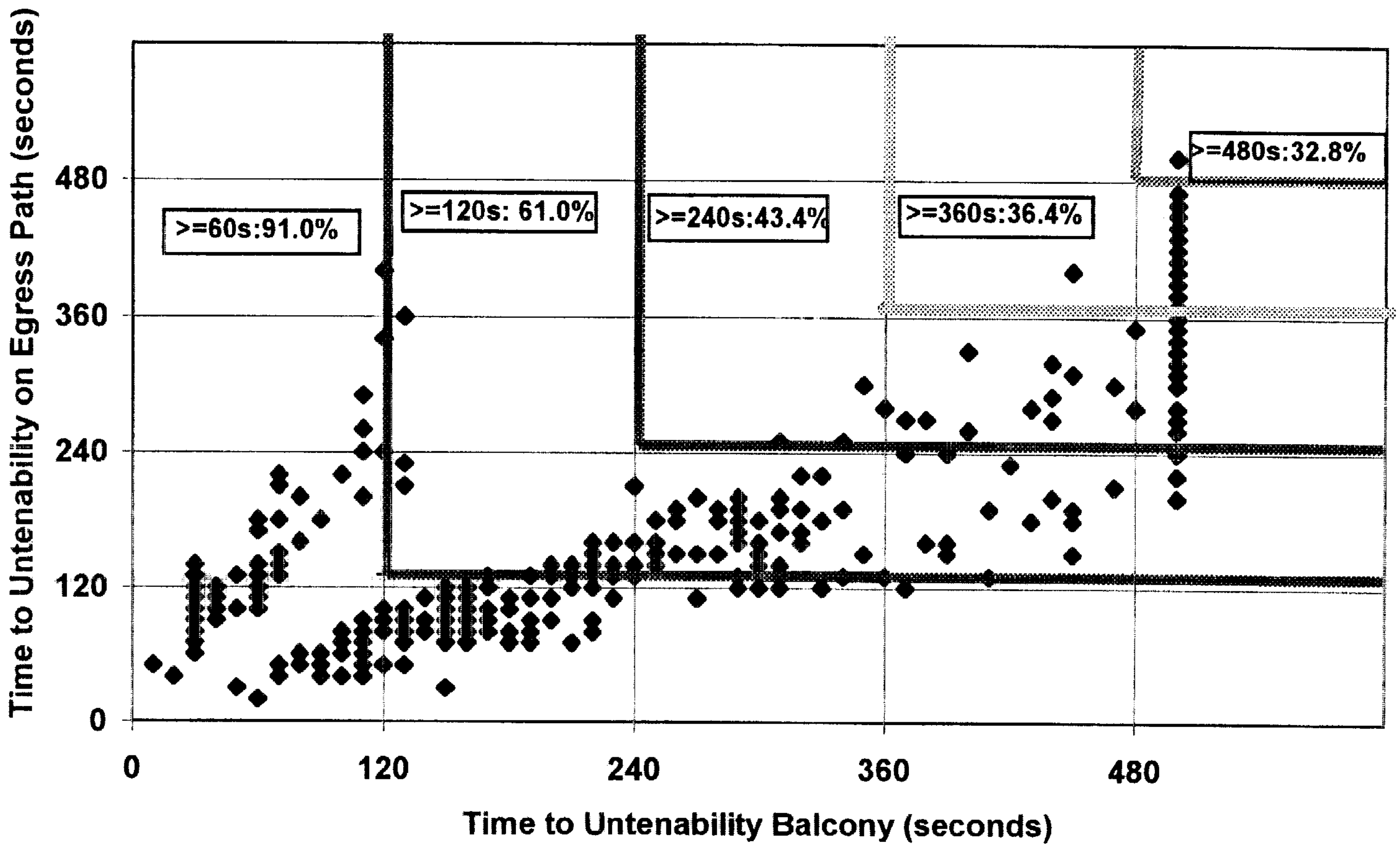

Figure 5-27. Time to Untenability (650C or 0.5 P-FED) Balcony and Egress Path, Sprinkler in Corridor and Entranceway

repeated for the bedroom, kitchen, and bathroom. Because the analysis for each of these rooms evaluates the minimum time to untenability in either of these rooms combined with the minimum time to untenability anywhere on the egress path, the living room, entranceway and corridor are subsets of these.

Figure 5-28 shows the cumulative distribution functions for egress from the balcony, bedroom, kitchen, and bathroom for the base case design of no sprinklers. Figures 5-29 and 5-30 show the cumulative distribution functions for egress from these rooms for Design 2, sprinklers in the corridor only; and Design 3, sprinklers in the corridor and entranceway. It can be seen that sprinklers in the corridor and entranceway provide less than 60s or more of the time to untenability at the 0.9 probability level for egress from the kitchen. Figure 5-31 shows time to untenability for egress from the balcony, bedroom, and bathroom based on Design 4, sprinklers in the corridor, entranceway, and kitchen. Design 4 provides greater than 60s of safe egress time at the 0.9 probability level.

We can see from Figure 5-32 that none of the designs evaluated using a min,min analysis provide a 0.9 probability of having 60 seconds or more of safe egress time; thus none are able to meet the probabilistic statement of performance.

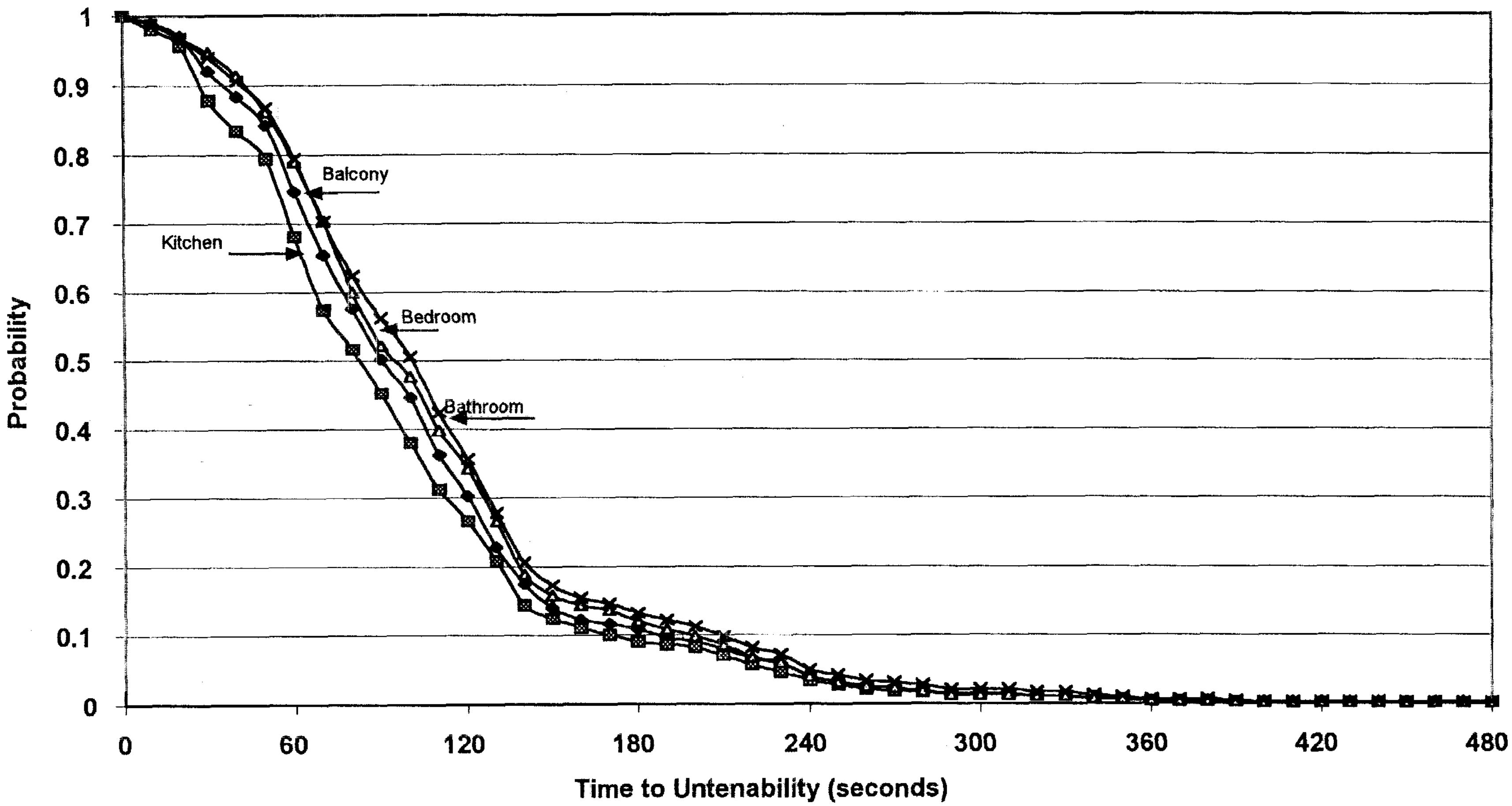

Figure 5-28. Time to Untenability (65°C and 0.5 P-FED) all Egress Paths, No Sprinklers

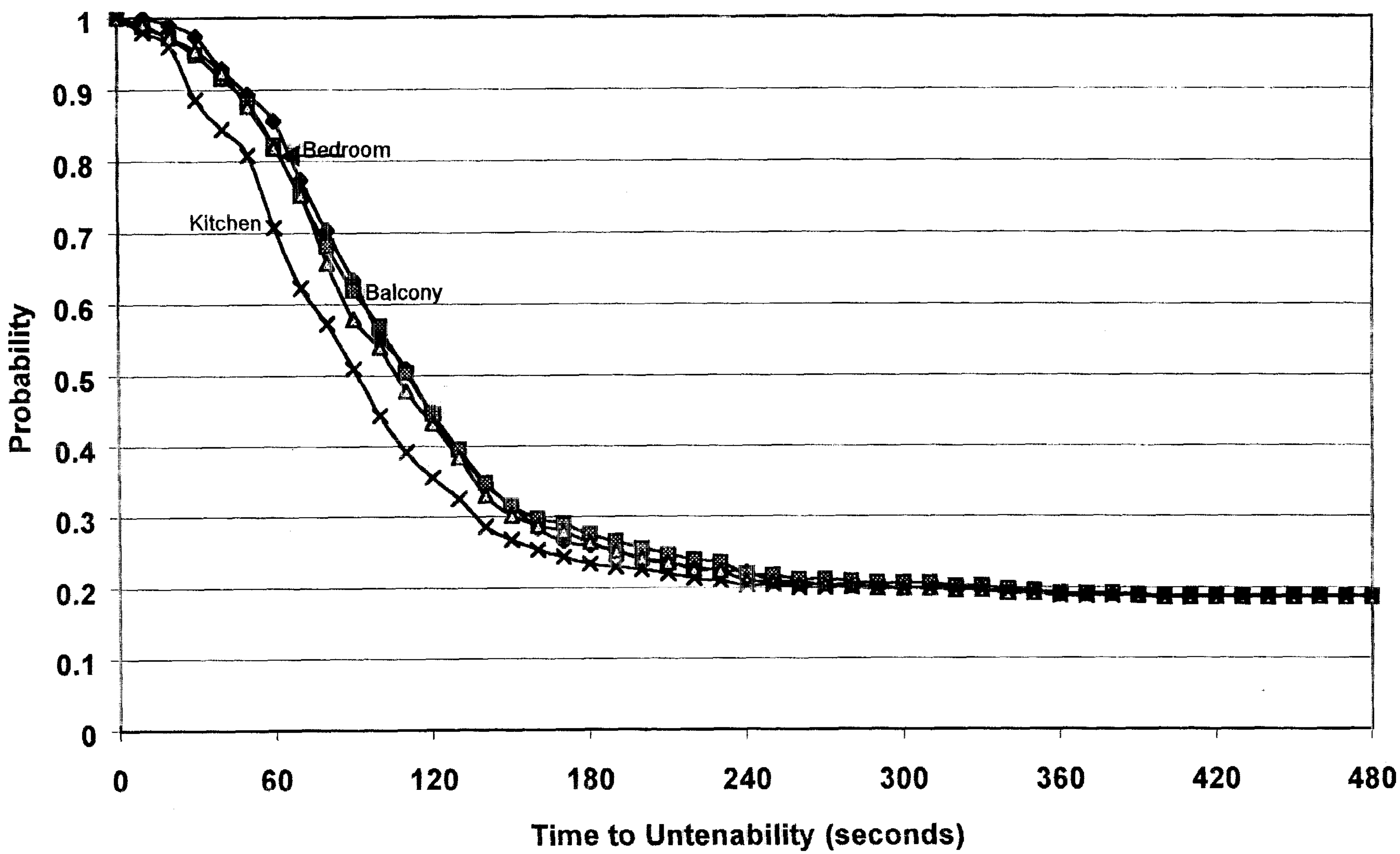

Figure 5-29. Time to Untenability (65°C and 0.5 P-FED) all Egress Paths, Sprinklers in Corridor

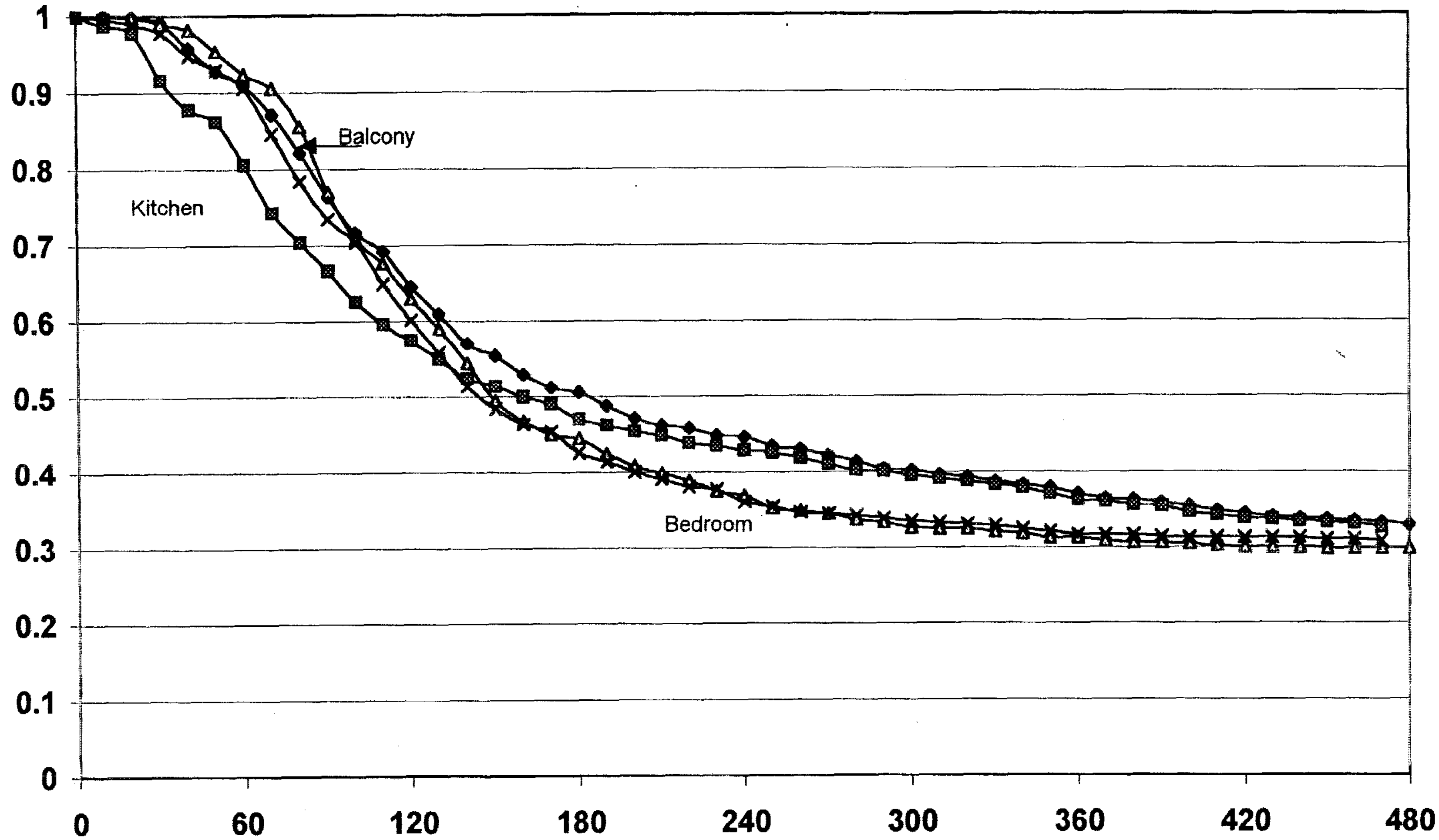

Figure 5-30. Time to Untenability (65°C and 0.5 P-FED) all Egress Paths, Sprinklers in Corridor and Entranceway

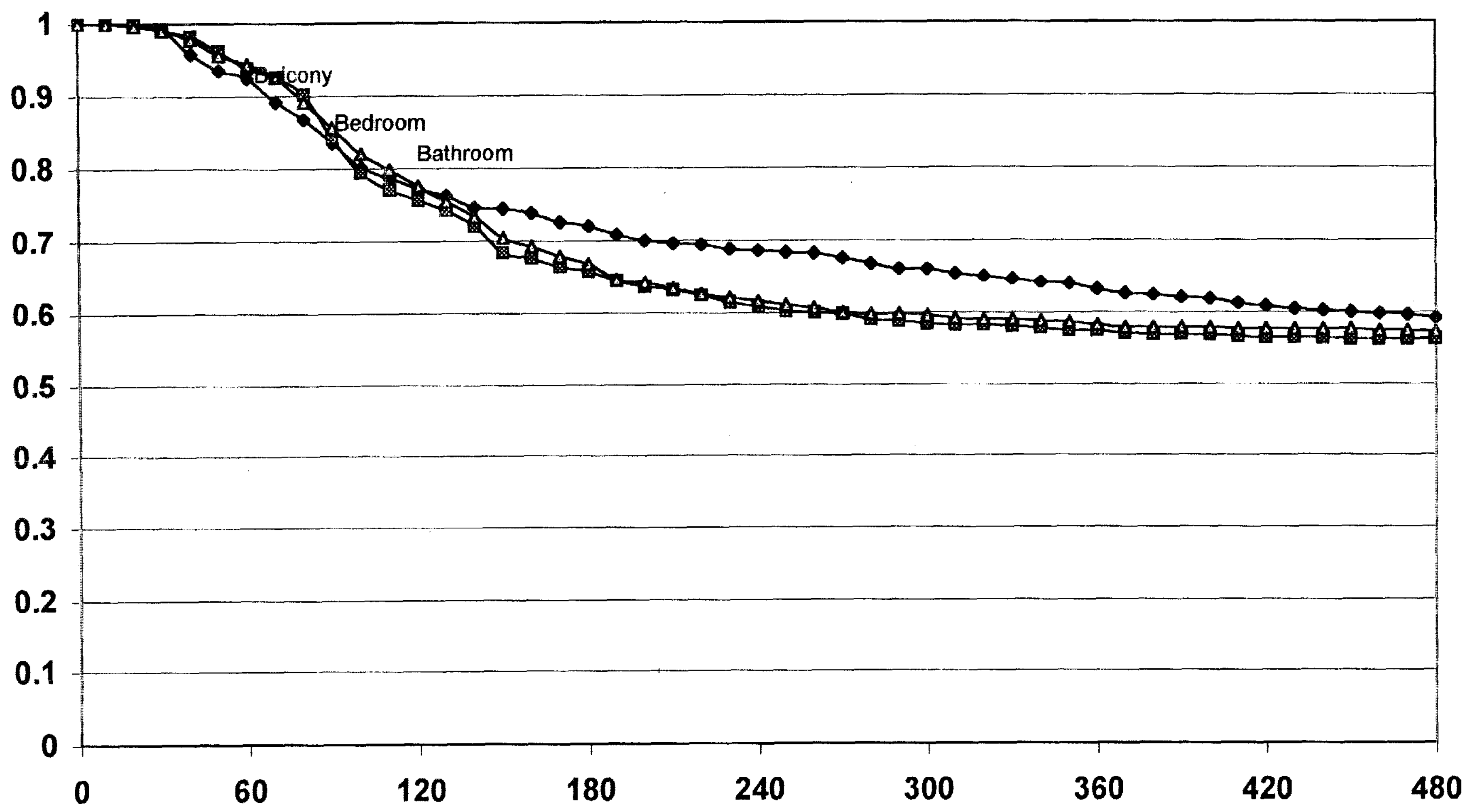

Figure 5-31. Time to Untenability (65°C and 0.5 P-FED) all Egress Paths, Sprinklers in Corridor, Entranceway, and Kitchen

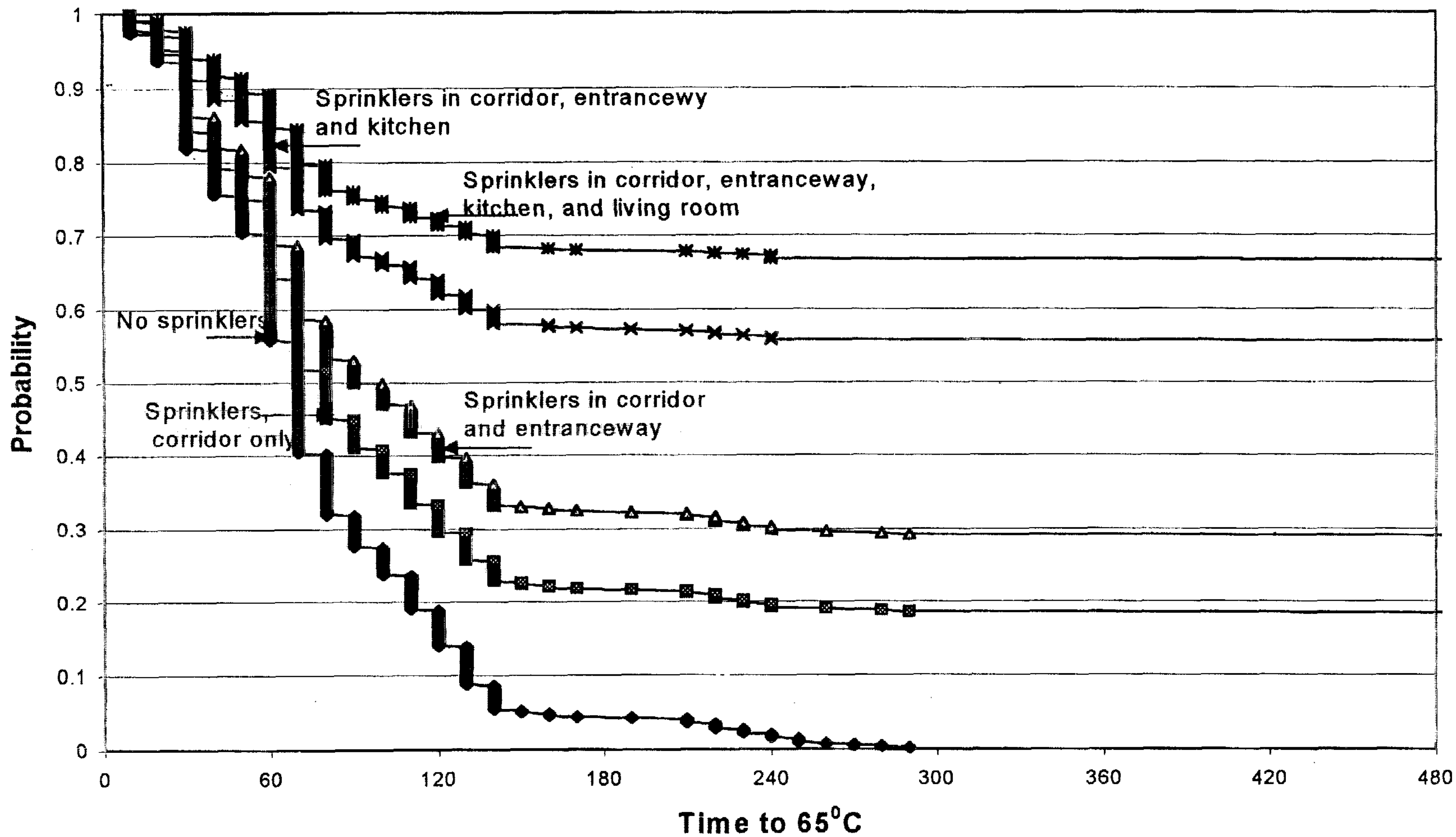

Figure 5-32. Time to Untenability, Min,Min Analysis For Designs 1 – 4

5.5 *Step 7h.* Evaluation of The Importance of Uncertainty

Importance analysis of time to flashover, incapacitation and lethal levels of temperature and gas concentrations, and optical density were conducted. Applying equation 3-1 discussed in Section 3.9.4, correlation coefficients with an absolute value of 0.08 or more are statistically significant at the 95% confidence level. Table 5-6 below shows the input parameters that were correlated at the 0.20 level or higher for at least one of these outcome criteria and Table 5-7 shows input parameters that were correlated at 0.08 or higher.

Table 5-6. Input Parameters Correlated at 0.20 or Higher

	mintimetoFLASH	*min,minPurser1.0*	*minmintimetoPurser.5*	*min,min 100C*	*min,min 65/338*	*min,min,OD0.5*
CV11	*-0.55*	*-0.76*	*-0.76*	*-0.62*	*-0.66*	*-0.56*
CV12			*-0.20*			*-0.59*
CHHOC						*-0.24*
FPOSZ		*-0.27*	*-0.28*	*-0.23*	*-0.26*	*-0.30*
CT						*-0.28*
CO			*-0.22*			*-0.59*
OD			*-0.21*			*-0.58*
alpha	*-0.52*	*-0.64*	*-0.62*	*-0.48*	*-0.51*	*-0.42*

Input Parameters correlated at 0.20 or higher are measures of the:

- percent openings of the door to the corridor (CV11)
- percent opening of the door to the outside of the building (CV12)
- heat of combustion (CHHOC)

- height of the fire off the floor (FPOSZ)
- rate of generation of products of combustion (CT, CO, and OD)
- rate of growth of the fire (alpha).

OD is defined as the ratio of mass of carbon to carbon dioxide produced by the oxidation of the fuel. CO is defined as the ratio of the mass of carbon monoxide to carbon dioxide produced by the oxidation of the fuel. CT is defined as the kilograms of toxic combustion products produced per kilogram of fuel pyrolyzed.

The correlation coefficients for the growth rate of the fire and the percent opening of the door to the corridor are highly correlated to all six performance criteria listed in Table 5-6. This means that the input parameters for opening of the door to the corridor and rate of growth of the fire (heat release rate) are the two most significant predictors of time to untenable temperature, time to untenable gas concentrations, loss of visibility due to optical density of the smoke, and time to flashover. The percent opening of CV12, the door to the outside of the building is significant for all but temperature predictions. The most significant of the input parameters are negatively correlated with each of the performance-criterion.

A negative correlation coefficient signifies that increases in the value of the input parameter results in a shorter time to reach the threshold level of a given

	mintimetoFLASH	min,minPurser1.0	minmintimetoPurser.5	min,min 100C	min,min 65/338	min,min,OD0.5
WIDTH2	**0.09**	**0.08**	**0.08**	0.05	0.05	**0.08**
DEPTH5	0.06	**0.13**	**0.14**	**0.11**	**0.11**	**0.10**
DEPTH6	**-0.09**	**-0.10**	**-0.10**	-0.08	-0.08	-0.05
DEPTH7	0.06	0.01	0.02	**0.10**	**0.09**	0.05
SILL1	**-0.09**	**-0.13**	**-0.13**	-0.06	-0.07	**-0.12**
HWITH10	-0.01	-0.03	-0.04	**-0.09**	-0.08	-0.03
SOFFITT10	0.07	**0.10**	**0.10**	0.06	0.07	0.06
HWITH11	0.03	**0.09**	0.08	0.03	0.03	0.01
SOFFITT11	0.08	0.08	**0.08**	0.03	0.03	**0.09**
SOFFITT12	**0.11**	**0.08**	0.08	**0.08**	0.08	0.07
CV1-1	-0.04	**0.21**	**0.20**	-0.01	-0.02	-0.02
CV2-1	0.05	**0.13**	**0.13**	0.05	0.06	**0.09**
CV3-1	-0.02	**0.08**	**0.08**	0.04	0.03	0.04
CV5-1	**-0.08**	**0.09**	**0.09**	0.07	0.08	0.07
CV6-1	**-0.13**	**0.10**	**0.10**	0.01	0.01	-0.01
CV7-1	**-0.13**	**0.10**	**0.10**	0.01	0.01	-0.01
CV8-1	0.06	**0.13**	**0.13**	**0.08**	0.08	0.06
CV9-1	**-0.13**	**0.10**	**0.10**	0.01	0.01	-0.01
CV11-1	**-0.55**	**-0.76**	**-0.76**	**-0.62**	**-0.66**	**-0.56**
CV12-1	**-0.09**	**-0.15**	**-0.20**	-0.05	-0.06	**-0.59**
CHHOC	**-0.14**	-0.04	-0.05	-0.05	-0.06	**-0.24**
CHGIT	**-0.09**	0.06	0.07	0.04	0.04	0.03
FPOSY	**0.29**	**0.25**	**0.25**	**0.49**	**0.44**	**0.26**
FPOSZ	-0.06	**-0.27**	**-0.28**	**-0.23**	**-0.26**	**-0.30**
alpha	**-0.52**	**-0.64**	**-0.62**	**-0.48**	**-0.51**	**-0.42**
Vol5	0.08	**0.12**	**0.13**	**0.12**	**0.12**	**0.12**
Vol7	0.05	0.03	0.04	**0.11**	**0.10**	**0.09**
open-out	**-0.15**	0.06	0.04	0.00	-0.01	**-0.16**

Table 5-7. Input Parameters with Statistically Significant Correlation Coefficients, 0.08 or Higher

performance criterion. For example, a faster growth rate of the fire and/or a more fully open door to the corridor would result in a shorter time to an upper layer temperature of 65°C or an optical density of 0.5/m.

These input parameters listed in Table 5-6 are largely the parameters we would expect *a priori* given our engineering judgement. Table 5-7 demonstrates the statistical significance of several additional input parameters that are worthy of further inquiry. Input parameters with correlation coefficients greater than the absolute value of 0.08 and less than the absolute value of 0.20 include the width and depth of the smaller rooms, and the percent opening of additional doors and windows. Correlations from additional case studies would be needed to make judgements about what parameters have significant uncertainty for different sets of building and occupant characteristics. Eventually, input parameters not statistically correlated will not need to be treated as uncertain and could be set to default or best-guess values.

The last three rows in Table 5-7 show the correlation of the performance criteria to combinations of input parameters; Vol5 is the volume of room five, the bathroom. Performance outcome criteria were correlated to the volume of each room. The volume of the bathroom, is statistically significant at the 95% confidence level for all the performance criteria evaluated. The volume of the corridor is statistically significant for predictions of temperature and optical density.

Insights are also gained by evaluation of the correlational analysis by module:

1. Weather Module

None of the variables in the weather module (internal and external temperature and pressure, wind speed, cosine of angle between wind direction and vent opening, relative humidity, or initial fuel temperature) had correlational coefficients that were statistically significant at the 95% confidence level. Further study is required; however it may be decided that best-estimate values are acceptable for these input parameters. In additional to further realistic case studies, it would be useful to determine parametrically what values of these parameters, if any, would cause a change in the acceptability of a design.

2. Building Geometry Modlue

None of the building geometry parameters were correlated at the 0.2 level or higher. However, several building geometry parameters were correlated at the 0.08 level or higher for prediction of some of the performance criteria. These included for example, width of room 2, the balcony, depth of room 5, the bathroom, and width and soffitt height of vent number ten.

Performance criteria were then correlated to a dummy variable for volume, represented by the width x the depth x the height of each room. As shown in Table 5-7, only the volume of room 5, the bathroom, and the volume of room 7, the corridor, were correlated to some of the performance criteria at a statistically significant level. The correlation coefficient for volume of room five is significant for all six of the performance criteria. The correlation coefficient for volume of room seven, the corridor, is statistically significant for prediction of temperature and optical density. Further data sets are needed, but implications are that if a 10% change in room dimensions does not change the results, then new simulations would not have to be run for small variations in building layouts.

3. Ventilation Module

The percent opening of the door to the corridor, CV-11 is highly correlated to predictions of all six performance criteria. Table 5-8 shows the average time to each of the key outcome criterion for the runs with the door closed (with a 0.1 leakage rate) vs. the average time to each of the thresholds for the runs with the door half-open and for the runs with the door closed. Correlation of the percent opening of the door to the outside of the building, CV12, with predictions of P-FED, flashover, and optical density are statistically significant. The percent opening of the door to the outside of the building is not significant for the prediction of time to untenable temperature. A combined input parameter, open-out, was made up of a sum of the total opening of vents to the outside. This parameter correlated significantly to time predictions of to flashover and optical density.

Vents to the outside of the building are negatively correlated with performance measures, i.e., the more outside air that comes in, the shorter the time to untenability. Some of the interior doors and windows were significantly correlated with times to FED and showed a positive correlation. The more open the interior vent, the longer the time to FED. FED is a ppm concentration of toxic gases so the positive correlation might be explained by a dilution factor, but further investigation through additional case studies is warranted.

Table. 5-8. Effect of Opening of Door to Corridor on Predictions of Key Outcome Criteria

Door to Corridor	Time to Flashover (seconds)	Time to P-FED .5 (seconds)	Time to P-FED 1 (seconds)	Time to 65 °C (seconds)	Time to 100 °C (seconds)	Time to OD (seconds)	Time to Layer 1.6 m (seconds)
Closed	467	412	391	157	115	88	83
Half-open	413	241	312	105	78	59	67
Open	294	183	169	52	36	28	51

4. Building Materials Module

To determine the significance of specification of building materials, five different materials were used. These were concrete, gypsum, hardwood, cellulose, and gyplast a two-layer specification of combined materials. A uniform distribution was used and approximately 100 scenarios were run with each of the five types of materials. The ceiling and walls were always made of the same material, but the floor materials may be different. Floor materials were limited to concrete, hardwood, and cellulose. The thermophysical properties of the enclosing surfaces are described by specifying the thermal conductivity, specific heat, emissivity, density, and thickness of the enclosing surfaces for each compartment. Values of thermal properties for materials are read from thermal database file within CFAST. The thermophysical properties are specified at one condition of temperature, humidity, etc.

Most of the heat conduction is through the ceiling, with an additional smaller effect through the walls. The floor contribution is expected to be negligible. Thus it is expected that specification of ceiling and wall materials will be a stronger predictor of time to untenable conditions. Table 5-9 shows the average time to each of the tenability criterion as a function of the ceiling and floor materials specified. Differences in time to threshold values of untenability are greater for the prediction of flashover, which occurs later in the fire development than for predictions of optical density, layer height, and time to 65°C. T-tests for statistical significance show that a difference of approximately seven seconds is significant at the 95% confidence level for these criteria.

Table 5-9. Time to Outcome Criteria (seconds) as a Function of Ceiling and Wall Material

Material	Time to Flashover (seconds)	Time to P-FED .5 (seconds)	Time to P-FED 1 (seconds)	Time to 65 °C (seconds)	Time to 100 °C (seconds)	Time to OD (seconds)	Time to Layer 1.6 m (seconds)
Concrete	451	316	294	78	107	60	66
Gypsum	383	293	271	70	96	55	60
Hardwood	416	341	316	85	117	56	77
Cellulose	303	307	288	70	93	59	66
Gypplast	443	336	316	90	125	69	70

Table 5-10. Time to Outcome Criteria (seconds) as a Function of Floor Material

Material	Time to Flashover (seconds)	Time to P-FED .5 (seconds)	Time to P-FED 1 (seconds)	Time to 65 °C (seconds)	Time to 100 °C (seconds)	Time to OD (seconds)	Time to Layer 1.6 m (seconds)
Concrete	396	313	292	103	76	59	69
Hardwood	392	326	304	115	83	60	66
Cellulose	398	317	295	107	78	61	66

5. Products of Combustion Modlue

As expected, input values of rates of generation of toxic products of combustion are significantly correlated to predictions of time to build-up of P-FED and optical density. Prediction of concentration of gases is naturally a strong function of the user-specified rates of production per unit of fuel burned. Better data sets are needed, and an information database should be integrated into CFAST. Currently, the user has to do fairly extensive research in order to obtain valid input data for various materials. Additional studies need to be conducted on the use of species generation rates from lab-scale tests in models of full-scale buildings, and the fire models should adjust production rates with changes in burning conditions.

6. Chemistry Module

The gas ignition temperature, lower oxygen limit, and molecular weight were not significant. These parameters are usually left at the default value be design engineers who do not have more specific information. Early indications from this one case study are that this practice may be sufficient.

7. Fire Parameters Module

The heat of combustion was significant for flashover and optical density. They were both negatively correlated, i.e. as the heat of combustion increased, the time to flashover and the time to 0.5 optical density decreased. The radiative fraction was not significant for any of these six performance criteria. This is not necessarily expected and needs further investigation. Future studies should incorporate stronger coupling of the radiative fraction with other fuel and burning parameters. The heat release rate was significant for all six performance criteria, as expected. The z-position, or height of the fire above the floor is significant as expected for all but flashover.

5.6 *Step 8.* Evaluation of Acceptability of Candidate Designs

The designs are judged against the probabilistic statements of performance. For this case study, the statement goal was "to provide a 0.9 probability of having 60 seconds or more to egress from the apartment before untenable conditions are reached" . Untenable conditions are defined as a temperature greater than 65°C or a P-FED greater than 0.5."

The base case design is not able to meet the probabilistic statement of performance because it only provides a 0.68 probability of having 60 seconds or more of time to untenability. Design 2, sprinklers in the corridor only, provides a 0.80 probability of having 60 seconds or more of safe egress time and also does not meet the criteria. Design 3, sprinklers in the corridor and entranceway, provides a 0.81 probability of having 60 seconds or more of safe egress time and does not meet our criteria. Design 4, sprinklers in the corridor, entranceway, and thus kitchen provides a 0.92 probability of having 60 seconds or more of safe egress and meets the probabilistic statement of performance for the egress path analysis. Design 4 would not meet the same probabilistic statement of performance for a min,min/room of origin analysis.

5.7 *Steps 9-10.* Selection of Final Design and Documentation

The only design evaluated that meets the probabilistic statement of performance is to provide residential fire sprinklers in the entranceway, corridors, and kitchen. This would be the least expensive design choice. If this were a real building design, other factors would be taken into consideration at this step. These would include the effect of other fire protection options in the building, cost, and owner preference. This type of analysis can inform those decisions by quantifying how much additional safety (for example, higher probability, more time) can be purchased for additional design options.

THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

6. A MUNICIPAL MODEL OF THE COST OF MANDATING RESIDENTIAL FIRE SPRINKLERS

ABSTRACT

This chapter presents a municipal model of the benefits and costs of mandating residential sprinklers. The cost per premature death averted and per life year saved from a residential sprinkler mandate as a function of house type and new and existing construction is calculated. House types examined are one and two-family homes, mobile or manufactured homes, and apartments. For these calculations, it is assumed that a smoke detector is either present or is installed at the time of sprinkler installation. Benefits attributed to residential sprinklers are those that can be expected above and beyond the benefits of an installed residential smoke detector. Calculations of cost-benefit are presented using national average numbers. These are compared to estimates based on region of the country and community size. Variability of the inputs is handled by taking 5 year averages of the data and using mean values. Uncertainty about the mean values is treated quantitatively and propagated throughout the analysis. This cost per life year saved for residential sprinklers is compared to other published costs per life year saved for other residential risk mitigation strategies for fatal injury reduction. This comparison can be used by a local government to determine where residential sprinklers should be mandated.

Two important findings are that residential fire sprinkler systems are cost-effective for new mobile homes and the need for coordination between the local water department and local fire department.

6. A Municipal Model of the Cost of Mandating Residential Fire Sprinklers

6.1 Introduction

6.1.1 Residential Losses

Residential fires only account for 22 percent of the total number of fires each year. However, residential fire deaths account for just over 80% of the total civilian fire deaths in the United States. Highway vehicle fires account for 12.6 % of civilian fire deaths, and non-residential fire deaths account for only 4 % of civilian fire deaths. From the period of 1989 - 1993 the mean number of residential fire deaths per year was 3,910 [NFPA, April 1996].

Residential fire injuries represent approximately 74 percent of the total civilian fire injuries per year. The mean number of U.S. civilian fire injuries over the period of study is 29,080. In addition, residential fires have double the number of firefighter injuries as compared to non-residential fires. Firefighter injuries in residential occupancies represent 57% of total fire fighter injuries, with a mean of 100,700 per year [USFA, 1993]. Residential property losses accounted for 4.3 billion dollars, or 53% of the total fire property damage and 63% percent of structural property loss.

It is the residential fire problem that most distinguishes our fire experience from that of other nations. Public places such as hotels, offices, or shopping malls are at least as safe in the United States as elsewhere [Schaenman, 1993]. Most of the nearly $22 billion dollars per year spent on fire protection for buildings, however, and most new code regulations are for non-residential occupancies. Non-residential deaths represent only 4% of the total. One potential reason for this is the different way the codes are developed and implemented in the United States as compared to other nations.

6.1.2 Residential Fire Protection Strategies and Sprinkler Mandates

Fire mitigation strategies can be categorized as prevention or suppression. The two major emphases in prevention are public fire education and built-in safety. Residential fire sprinklers, although a form of suppression, are typically categorized as built-in safety.

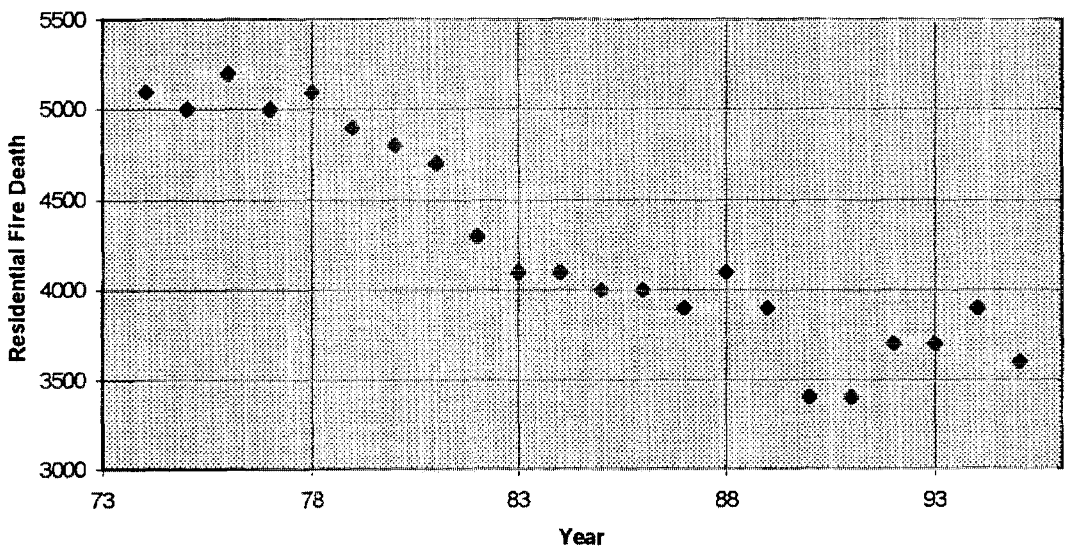

Figure 6-1. Trends In Home Fire Deaths

There was a significant drop in the residential fire death rate in the late 1970's to early 1980's, shown in Figure 6-1 [Accident Facts, 1996]. This decline is attributed to a large degree to the invention and widespread adoption of residential smoke detectors, which were invented in 1965. In the mid 1970's, GE got into the business with extensive marketing and the price dropped into the impulse buying category. Sales climbed between 1975 and 1980, with a peak in 1978 of 14 million per year. Detector sales remain at 8-10 million per year today [Bukowski, 1996]. Many studies have been published estimating the cost of residential smoke detectors. It has been reported that smoke detectors have a net benefit cost of zero dollars per premature death averted [Jensen et al., 1989].

Because smoke detectors made such a large impact, it is widely believed that other fire safety systems such as sprinklers are the next logical step. Automatic sprinklers can extinguish a fire before life-threatening conditions are reached in the room [Notarianni, 1990]; therefore, they have the potential to prevent more deaths than smoke detectors alone. People unable to egress from the building such as the physically or mentally disabled, children, the elderly, and those sedated from alcohol or drugs may particularly benefit from automatic sprinklers, in addition to property savings. However, a study of benefits and costs should be conducted before residential sprinklers are implemented. A description of the physical system is presented in the next section, followed by presentation of a benefit-cost model.

There are many building and fire code mandates passed to help mitigate the fire problem in the United States, both industrial and residential. The National Fire Protection Association (NFPA)[1] publishes over 200 fire codes and standards. Determining the benefits and costs of these standards is a difficult task that requires good data and models. One current residential fire mitigation strategy under consideration in numerous communities across the nation is residential fire sprinkler systems. NFPA 13R covers the installation of residential fire sprinkler systems. This paper develops a municipal model of the benefits and costs of residential fire sprinkler systems and compares the cost per premature death averted of residential sprinklers to other residential fatal injury reduction interventions published.

6.1.3 Objectives of this Work

Previous benefit-cost studies of residential fire sprinkler systems were conducted in the 1980's. One of the first and most widely cited studies was performed at NIST [Ruegg, 1984]. This study was conducted from a homeowner's perspective, used national average probabilities and values, and did not treat uncertainty. The study presented here will be conducted from the standpoint of a municipal government. The model combines several input scenarios including national region, community size, and home type to determine the cost per premature death averted and life-year saved and treats uncertainty quantitatively.

[1] The National Fire Protection Association (NFPA) is an association of over 66,000 fire protection professionals. Since 1896, one of the primary purposes of the NFPA has been to develop and update the standards covering all areas of fire safety. However, the NFPA has no power to police or enforce compliance with NFPA standards.

The study will:

- calculate national average sprinkler costs in dollars per life-saved and dollars per life-year saved;
- determine the costs of residential sprinklers as a function of region, community size, house type, and house age;
- evaluate the costs of a partial, non code complying residential fire sprinkler system;
- show the importance of fire and water department coordination; and

6.2 Description of Residential Sprinkler System

A residential fire sprinkler system is composed of a water supply, underground and overhead-piping connecting the water supply to the sprinkler heads, sprinkler heads and associated hardware such as control valves, check valves, and alarms. Various types of metal or plastic pipe may be used in construction of the sprinkler system. In this study, only polyvinyl chloride (PVC) piping is evaluated.

Polyvinyl chloride pipe is selected based on a prior NIST study, "Comparison of Fire Sprinkler Piping Materials: Steel, Copper, Chlorinated Polyvinyl Chloride, and Polybutylene in Residential and Light Hazard Installations" [Notarianni and Jackson, 1994]. Plastic pipe is lower in weight, cost, susceptibility to corrosion, and installation time than metal pipe. It is flexible. Polyvinyl chloride was selected over polybutalene because it can withstand a higher maximum ambient temperature and is approved for all residential occupancies.

The standard for installation of fire sprinkler systems is NFPA Fire Protection Code 13 [NFPA 13, 1996], originally produced in 1896. In 1975, NFPA 13D, was first released for One- and Two-Family Dwellings and Manufactured Homes. NFPA 13R covers Residential Occupancies Up to and Including Four Stories in Height [NFPA 13R, 1996]. NFPA 13E, Guide for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems [NFPA 13E, 1995].

Automatic fire sprinkler systems often require separate water main taps, although a common supply main for sprinklers and domestic use is permitted if combined demand can be meet by piping system components. In some cases, a residential fire sprinkler system may require a new tap to the public water supply or an increase to the size of the existing tap. Local water departments may also require the use of back-flow preventors on residential sprinklers. A new tap fee can cost over $2,000 dollars. If a back-flow preventor is required by the water department in lieu of a standard single or double chek valve, another $1,000 to $1,500 dollars is added to the system costs, effectively doubling them. A study of risks and benefits with various levels of back-flow prevention illustrated that the waterborne illness risk would remain essentially unchanged if residential sprinklers systems were installed with a simple check-valve device [Hart, 1996].

Sprinkler heads are individually heat actuated by either a bimetallic fusible element or a glass bulb. The actuation of a sprinkler is a function of maximum ceiling temperatures. Typically residential fire sprinkler activation temperatures are 57 ° C to 77 °C. A local water flow alarm is provided on all systems. Design discharge for a residential fire sprinkler system is 13-18 gpm/sprinkler. The maximum area protected by a single sprinkler head is 144 ft^2. The number of design sprinklers is all sprinklers within a compartment up to a maximum of four sprinklers. Water demand is found by multiplying the design discharge by the number of design sprinklers.

Accidental discharge and leakage of sprinklers are both very low. One study has approximated the leakage rate of residential sprinklers as one per year per 3 million sprinklers. When leakage does occur, it is generally limited to one sprinkler. In the case of a fire event, only the individual sprinkler heads, heat actuated and in the vicinity of the fire, will dispense water. In the absence of sprinklers, water damage from conventional fire fighting would be much greater.

6.3 Description of Municipal Model

The model was created using a commercial software package, Analytica.[2] The software is described in the Analytica Users Guide [1996]. The model(s) calculates the cost in dollars per premature death averted from installation of residential sprinkler systems. The model also calculates dollars per life-year saved. Benefits of residential sprinklers accounted for in the model include the reduction in expected value (EV) of occupant and firefighter injuries, and the

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[2] Marketed by Lumen Decisions Systems, Los Altos, CA

reduction in EV of direct and indirect losses. Other potential benefits from a residential sprinkler mandate include savings on fire department costs and savings on costs associated with building construction for fire protection. These were not included in the first set of calculations but are considered at a later stage. Costs include installation costs and annual maintenance costs.

6.3.1 Structure of Model

An influence diagram for the model is shown in Figure 6-2. The model has five types of components. A parallelogram-shaped node depicts an index variable, which is used to define a dimension of an array. There are four index variables: region of the country, community size, house type, and house age. Each index is presented in Table 6-1. There are a total of 192 combinations of indices. Regions of the country are chosen to correspond with the Census Bureau designations.[3] Community sizes are in accordance with the way the national fire statistics are calculated. House type and house age index variables provide the decision-maker with information helpful in setting more targeted legislation.

[3] Census defined regions are West, Northcentral, South, and Northeast. States in the West region are Washington, Oregon, California, Nevada, Idaho, Montana, Wyoming, Utah, Colorado, Arizona, New Mexico, Hawaii, and Alaska. Northcentral states are North Dakota, South Dakota, Nebraska, Minnesota, Kansas, Iowa, Missouri, Illinois, Indiana, Wisconsin, Michigan, and Ohio. Southern states are Texas, Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Georgia, Kentucky, West Virginia, Virginia, North Carolina, Florida, Delaware, and Maryland. Northeastern states are Pennsylvania, New York, New Jersey, Connecticut, Rhode Island, Massachusetts, New Hampshire, Maine, and Vermont.

A hexagonal node depicts an objective variable. There are four objective variables in the model. The first calculates the total annual installation and maintenance costs. Cost data was taken from several HUD/FEMA studies [FEMA,89a,89b,90a,90b]. The second calculates the total annual expected benefits. The third objective variable is the dollars per premature death averted, and the fourth is the dollars per life-year saved.

Table 6- 1. Index Variables

Index Variables			
Region of Country	**Community Size**	**House Type**	**House Age**
Northeast	250,000 or more	One- and Two-Family Dwelling	New
North Central	100,000 to 250,00	Multi-Family	Retrofit
South	50,00 100,000	Mobile Home	
West	25,000 to 50,000 10,000 to 25,000 5,000 to 10,000 2,500 to 5,000 2,500 or less		

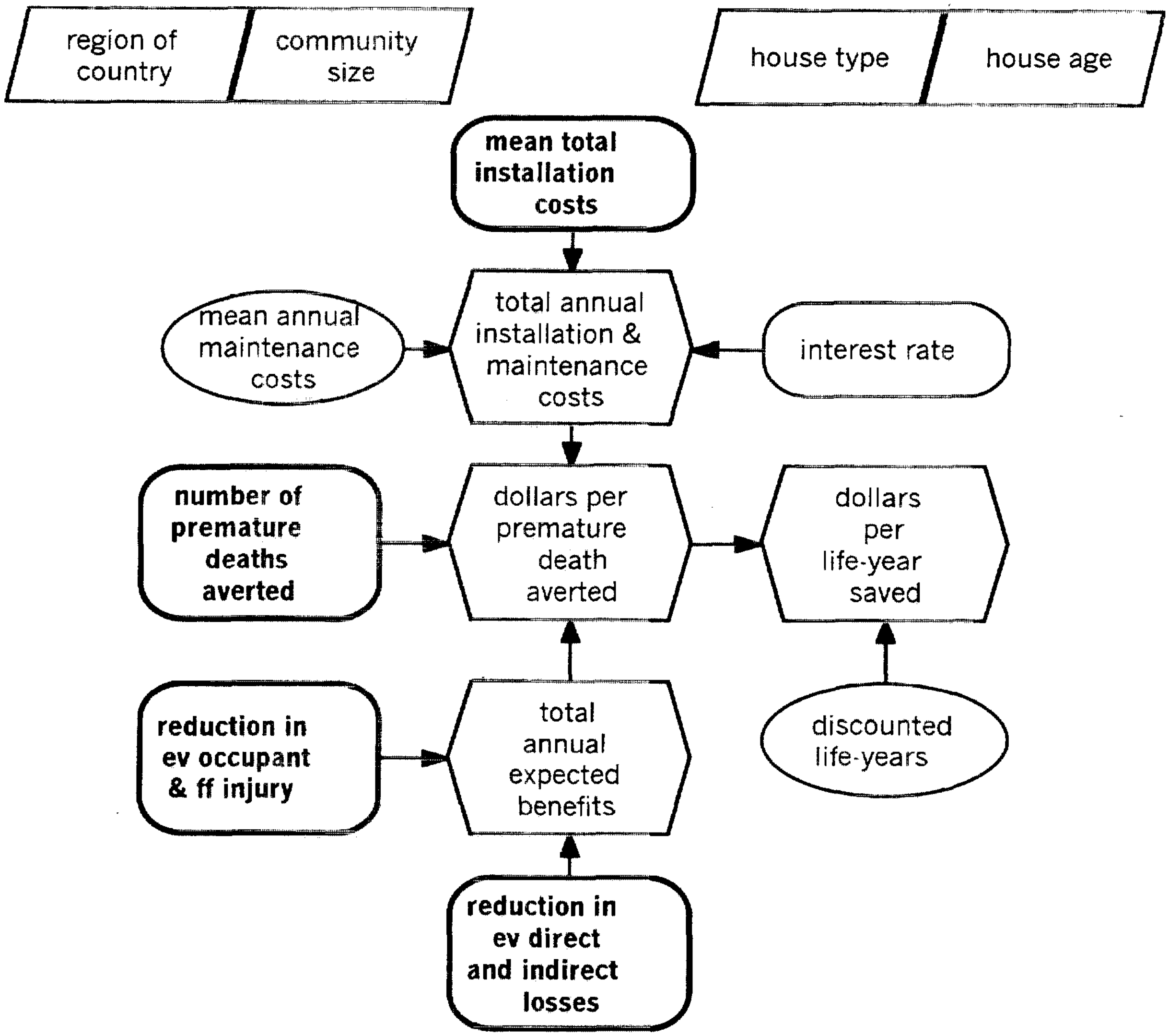

Figure 6- 2. Influence Diagram

An oval node depicts a chance variable. Chance variables are uncertain. All chance variables, the one in the main module and the many more in the modules, are defined as mean values taken over a five-year period from 1989-1993. Therefore, variability is not a factor in the analysis; however, there is uncertainty about the mean. Annual maintenance costs represent a preventative maintenance program consisting of an inspection by a sprinkler of plumbing contractor. The inspection is assumed to entail flow-tests of sprinkler heads, test of the alarm system, inspection of all valves, and replacement of parts if needed. The mean of the annual maintenance cost thus equals between $30 and $70 dollars.

A rounded, thin-outline node depicts a general variable. The two general variables defined in this model are the interest rate and the discounted life years per premature death averted. Interest rate was set to vary parametricaly from 6% to 10% with a 2% step.

A rounded, thick-outline node depicts a module, which is a collection of nodes organized as a separate diagram. The model contains four modules which calculate the following costs and benefits: A) total annual installation and maintenance costs; B) the number of premature deaths averted; C) the reduction in EV of occupant and firefighter injuries; and D) the reduction in EV of direct and indirect losses. A full description of the module that calculates the number of premature deaths averted is presented below and includes the type and source of the data.

In order to understand the calculation of the number of premature deaths averted, it is necessary to understand who dies in home fires. Fire experience varies by region of the country. Among the factors that contribute to these differences are: A) climate; B) size of community; C) percent of population in urban and rural areas; D) population age distribution; E) percent of population below poverty level; F) percent of population with high school education; and G) housing characteristics (e.g., age of structure, type of construction, and type of heating equipment). By far the factors most strongly correlated with differences in regional fire death rates are poverty and education.[4] Variables such as the age of housing, climate, number of people per household, and percentage of manufactured homes were not found to be highly correlated with the regional fire death rates. The civilian fire death rates per million population by region and community size, 1989-1993 averages, are shown in Table 6-2.

Fire death rates vary from 9.5 deaths per million population in a community size of 50,000 to 100,000 in the west to 48.9 deaths per million population in a community the size of less than 2,500 in the South. The Northeast has the highest death rates for communities of 50,000 or more, while the South has the highest rates for small and medium size communities. Fire death rates in the West were below the National average in all but one community size.

[4] In an analysis conducted by NFPA, the education variable was able to explain 48% of the variation in state fire death rates and the poverty variable was able to explain 38% of the variation [NFPA state report]. The ten states with the highest percentages of people age 25 or older that lack a high school education all rank among the 13 highest fire death rates.

Table 6-2. Civilian Fire Death Rates per Million Population by Region and Size of Community, 1989-1993 Average

Population of Community	Nationwide	Northeast	North Central	South	West
250K+	21.1	34.0	30.8	19.8	11.9
100K to 250K	17.4	26.0	21.1	18.6	9.9
50K to 100K	15.6	19.5	15.3	19.4	9.5
25K to 50K	13.7	12.8	9.7	22.3	9.7
10K to 25K	16.0	13.0	14.7	20.7	14.3
5K to 10K	21.3	13.3	21.3	26.1	24.4
2.5K to 5K	24.0	20.8	24.6	35.3	14.4
< 2.5K	38.9	37.6	34.3	48.9	35.9

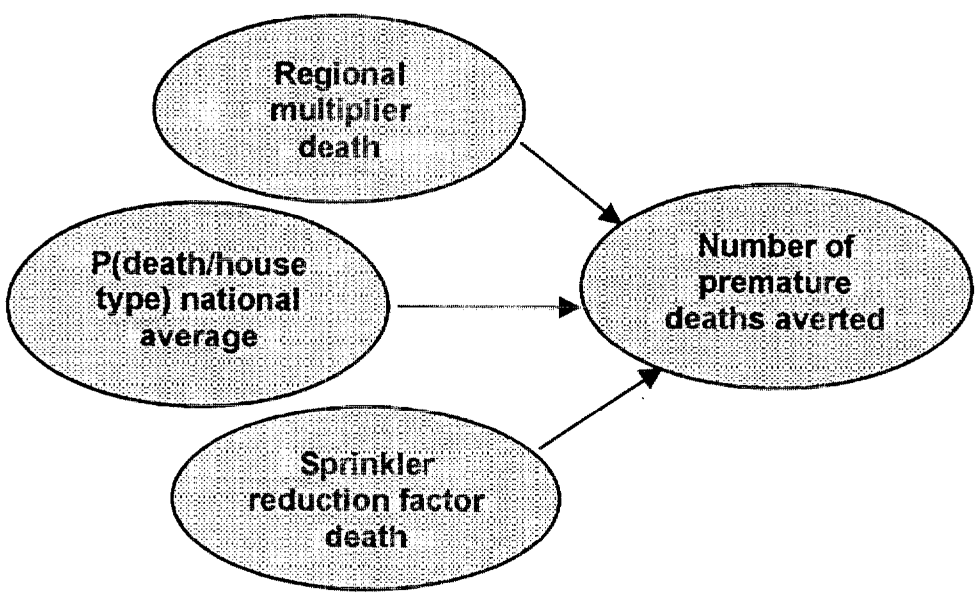

Figure 6-3. Module – Number Of Premature Deaths Averted

The number of premature deaths averted is calculated by multiplying the national average probability of death given house type by the regional/community size multiplier for death by the sprinkler reduction factor. The probability of death given the house type is defined as the number of fire deaths in a given house type divided by the number of households of that house type nationally. Regional multipliers are relative to the national average death rate and are taken from [Karter, March 1995] and calculated from Figure 6-3 above. The sprinkler reduction factor is taken from NFPA data comparing residential fires in sprinkled homes with residential fires in non-sprinkled homes [Hall, June 1995]. All values are mean annual values averaged over a five-year period. Uncertainty bands represent uncertainty about the mean. Similar calculations are performed for other modules.

6.3.2 Treatment of Variability and Uncertainty

6.3.2.1 Inter-Year Variability in the Fire Loss Statistics

To conduct a cost-benefit study of residential fire sprinkler systems, many fire statistics (e.g., death rates, injury rates, and average direct dollar losses) are needed as inputs. National average values of these numbers are often used in these analyses. For example, the national average value for the residential death rate would be equal to the number of residential fire deaths nationally divided by the number of occupied residential units. The actual fire death rate will vary with a number of parameters. The U.S. National Fire Protection Association publishes death rates discretized by three of our four index variables: region of the country, community size, and house type.[5] There are four regions of the country, eight community sizes, and three house types. Thus, the death rate used in these calculations is a 4 x 8 x 3 matrix consisting of 96 values for each death rate. Two examples are the death rate in mobile homes in a community size of 2,500 or less in the South and the death rate in a one- or two-family dwelling in a community size of 25,000 to 50,000 in the West.

6.3.2.2 Yearly Variability in the Fire Loss Statistics

It is important to differentiate between variability and uncertainty. Variability in the fire statistics from year to year arises because of the randomness of occurrence of fire events. For instance, in one particular year, several large loss fires may occur followed by few or none the next year. In this study, because we are interested in benefits and costs over the life of a fire sprinkler system, mean yearly values were chosen. Yearly variance in the fire loss experience for deaths, injuries, property loss, and indirect losses is thus accounted for by taking mean yearly values over a five year period. Mean values were calculated from the 1989-1993 data.

6.3.2.3 Uncertainty in the Fire Loss Statistics

Uncertainty in the fire loss statistics exists due to the impossibility of a full and accurate accounting of all fires and all fire losses. Mathematical techniques are

[5] Karter, Michael Jr., U.S. Fire Experience by Region, 1989-1993, National Fire Protection Association, Quincy, MA, 1995.

thus used to provide estimates.[6] Uncertainty in the fire data is represented as uncertainty about the mean values. An expert elicitation of the chief statistician of NFPA[7] was conducted to set the uncertainty bands for the fire statistics.

6.3.2.4 Uncertainty in Other (Empirical) Model Inputs

Uncertainty in the cost data and parameters such as the sprinkler reduction factor were determined by bounding. For example, uncertainty in the sprinkler reduction factor arises because of the small number of fires occurring in homes with automatic sprinklers installed. Data from other occupancies were used to bound the uncertainty.

6.3.2.5 Propagation of Uncertainty

Once the uncertainties in the model inputs have been expressed, the question becomes, "How can we propagate these uncertainties through the model to discover the uncertainty in the predicted consequences?" In this analysis a Monte Carlo simulation was used. A value for each input is randomly selected from its actual probability distribution. From these values, a value for the outcome criteria is calculated. This process is repeated many times, resulting in a probability distribution for each outcome variable.

6.3.3 Value of a Life

For any cost-benefit analysis regarding health and safety, one of the most highly contentious points is setting a "value of life" or more accurately, the rate of

[6] Hall, John, Jr., and Harwood, Beatrice, The National Estimates Approach to U.S. Fire Statistics, Fire Technology, May 1989.
[7] Hall, John, Jr., Personal Communication, Uncertainty Bands, 1996.

investment to avoid low probability uncertainties. Economists have come up with various ways of estimating this value. These include willingness to pay for safety devices and income-based estimates.[8] All of these methods remain highly debated. For this study, the problem of establishing a "value of life" was avoided by means of careful selection of the *outcome criteria*. By selecting the outcome criteria to be dollars per premature death averted and dollars per life-year saved, no explicit "value of life" needs to be inputted.

6.4 Results

6.4.1 National Average Calculation

The national average cost of residential sprinklers, in dollars per premature death averted, was calculated to be 7.3 million dollars at the median value. The probability bands at 8%[9] range from a 0.05 value of 4.2 million to a 0.95 value of 10.7 million dollars (Table 6-3).

Table 6-3. Dollars Per Premature Death Averted National Average Calculation

Probability	Dollars
0.05	4.2 M
0.25	5.6 M
0.5	7.3 M
0.75	9.3 M
0.95	10.7 M

[8] Viscusi, W.K., Chapter 4: A Survey of Values of Risk to Life and Health, "Fatal Tradeoffs: Public and Private Responses to Risk, pp. 51-54, Oxford, 1992.

Based on a national average calculation, residential fire sprinklers with a median cost of 7.3M dollars would not typically fall into the cost-effective range generally accepted. The lower dollar limit is considered to be less than 3 million dollars per premature death averted, based on other applications [Viscusi,1992]. The following sections show the results of the benefit-cost analysis for each combination of the indices and reports general trends and conclusions. Considering the fire death and other regional statistics, we expect to find significant differences.

6.4.2 Indexed Calculations

Calculations conducted by region, community size, house type, and house age provided good insight into the cost of residential fire sprinkler systems and their impact on the residential fire problem. The cost of residential fire sprinkler systems was calculated for a complex matrix of four regions of the country, eight community sizes, three house types, and two house ages. A total of 192 combinations of indices was evaluated. This section presents some general results and trends as well as results for each housing type and age.

6.4.2.1 General Results and Trends

A study of the results for the 192 combinations of the indices shows some general trends. For all three home types, new construction was a lower cost in dollars per premature death averted than retrofit for the same home type. This is

[9] An interest rate of 8% is used in this analysis. A sensitivity analysis was conducted to determine if use of an interest rate of 6% or 10% would cause switch over in the decision. None of the basic conclusions of the report change.

due to the higher installation costs for existing homes. In order of costs, one and two family dwellings were more costly than multi-family dwellings; multi-family homes were, in turn, more costly than mobile homes. These two points are demonstrated by the bar graph in Figure 6-4 for a medium size community (population 10,000 - 25,000) in the South, and in Figure 6-5 for a larger community (population 50,000 - 100,000) in the West. For both communities, the cost for a new home is always lower than the cost for an existing home.

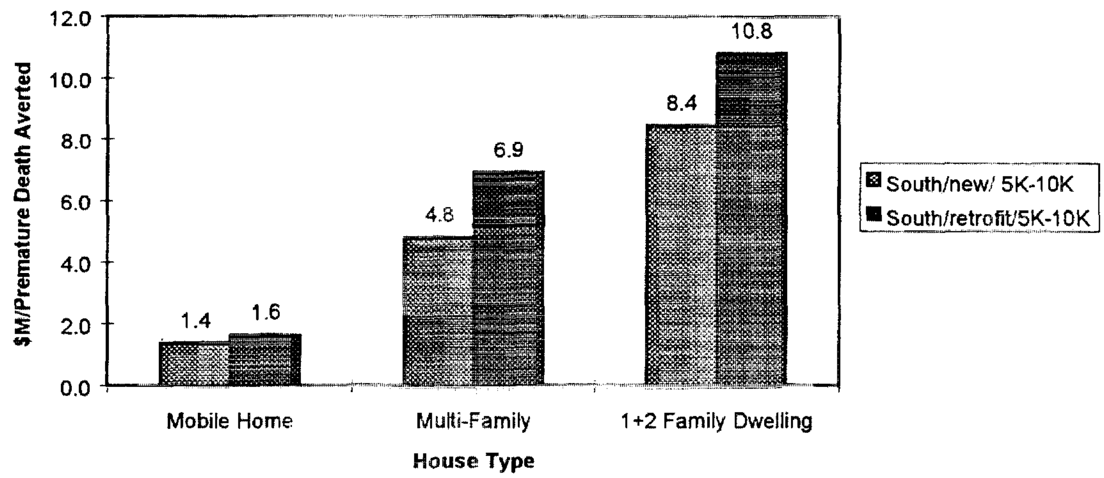

Figure 6-4. M$/Premature Death Averted, Small Size Community in the South

A third point is that costs for residential sprinklers in the West are higher than in the other three regions across all community sizes. Costs in the Northeast and North Central follow a trend for all house types where costs in the Northeast start off lowest of all regions for the three largest community sizes, population 50,000 and above. After this point, the South drops to the lowest costs and remains there throughout the smallest community size. At 25K and smaller, the North

Central drops below the Northeast and remains lower than Northeast and higher than South. The West is consistently higher than all regions for all community sizes and all house types and house ages. These trends can be seen in Figure 6-6 for new mobile homes. However, the same trends hold for all house types and house ages.

The costs vary from 1.4 million per premature death averted to 35.1 million (for a new mobile home in a small community in the South and a retrofit of a one and two family dwelling in a medium size community in the west, respectively). Clearly if residential fire sprinkler systems are not cost-effective for mobile homes, they will not be cost-effective for other house types. Results for the mobile home calculations are presented first.

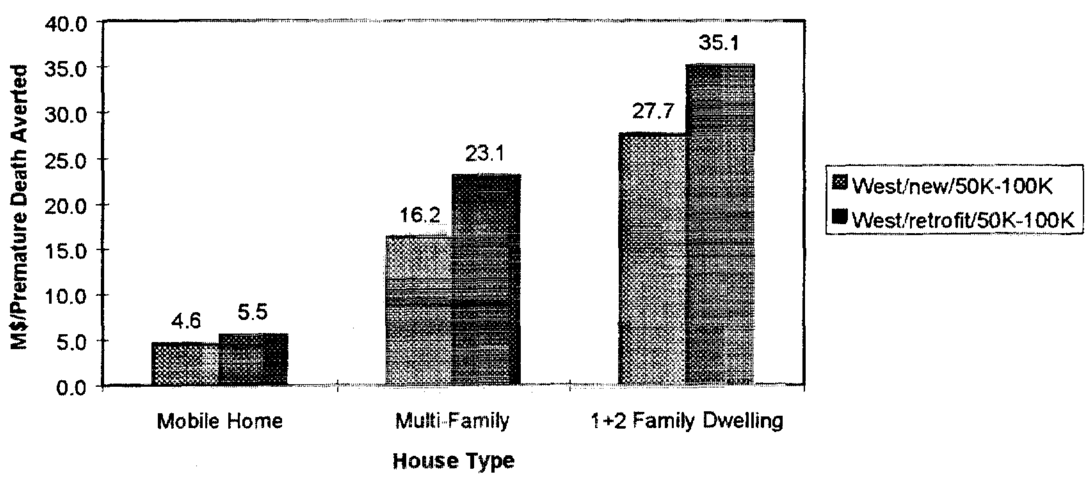

Figure 6-5. M$/Premature Death Averted, Medium Size Community in the West

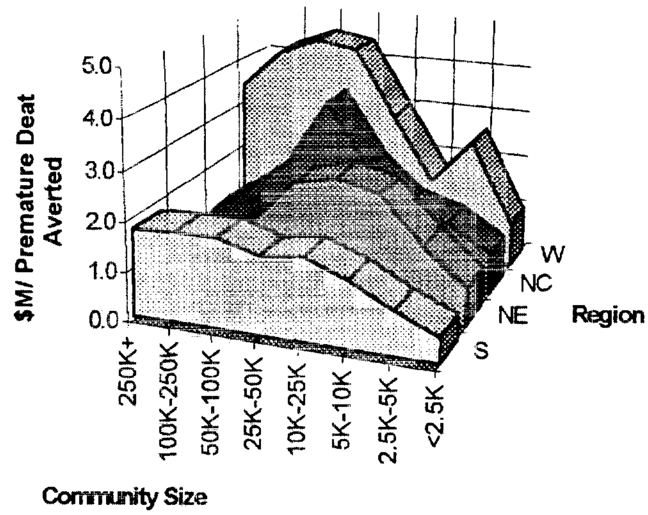

Figure 6-6. $M/Premature Death Averted Residential Sprinklers in New Mobile Homes

6.4.2.2 Mobile Homes

The cost of residential fire sprinklers for new mobile homes is presented in Figure Figure 6-6 in terms of dollars per premature death averted. All regions and community sizes have a cost of three million dollars or less except for the larger communities in the West. To place these costs in context, in the next section the costs are compared to other residential interventions aimed at fatal injury reduction.

6.4.2.3 Multi-Family and One- and Two-Family Dwellings

Residential fire sprinkler systems in multi-family and one and two family dwellings cost as much as 3-6 times the price per premature death averted as do their counterparts installed in mobile homes. At $110,000 per life-year saved, residential fire sprinklers would not be cost-effective for all multi-family or one and two family dwellings in any of the 32 community size/regional categories evaluated for either new or retrofit construction. Retrofitting fire sprinkler systems in a one and two family dwelling can cost up to 35.1M dollars per premature death averted. Given the high cost of residential fire sprinkler systems for many house types in many communities, it is worth evaluating the cost-effectiveness of a partial sprinkler system.

6.4.3 Comparison to other Life-Saving Interventions

An article in Risk Analysis [Tengs, 1995], "Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness," identified over 500 life-saving interventions, reporting them in terms of dollars per life-year saved. The interventions were classified in four-ways: 1) Intervention Type (Fatal Injury Reduction, Medicine, or Toxin Control); 2) Sector of Society (Environmental, Health Care, Occupational, Residential, or Transportation); 3) Regulatory Agency (CPSC, EPA, FAA, NHTSA, OSHA, or None); and 4) Prevention Stage (Primary, Secondary, or Tertiary). The accuracy of the results is limited by the accuracy of the data and assumptions in each original analysis, but are believable within an order of magnitude. The interventions range from those saving more resources than they consume, to those costing more than 10 billion dollars per year of life saved.

A comparison of the cost per life-year saved for residential sprinklers in new and retrofit mobile homes was compared to other residential fatal injury reduction interventions.[10] Figure 6-7 shows this comparison. The median cost per life-year saved for residential fatal injury reduction was $36,000 (n=30). The mean cost-effectiveness of proposed government regulations for certain agencies were also reported. For the Consumer Product Safety Commission, the mean was $68,000/life-year saved (n=11). About 32 percent of all interventions fell at or below this level. Clearly, the costs of residential sprinklers in mobile homes, both new and retrofit are in line with these figures.

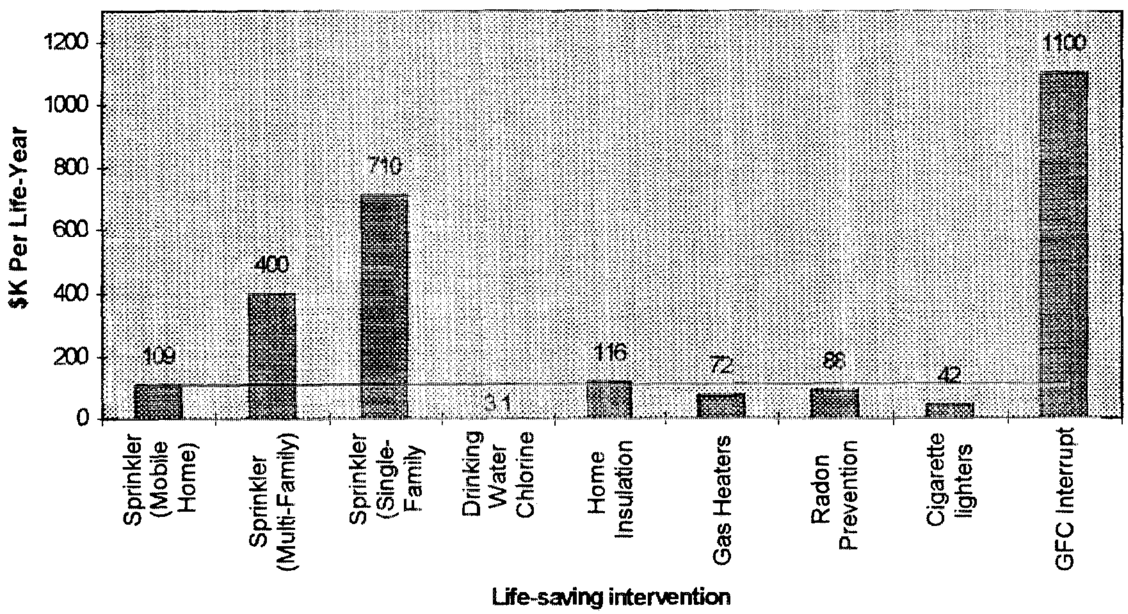

Figure 6-7. Comparison of Cost of Residential Fire Sprinkler Systems with Other Residential Life-Saving Options

[10] Life-years saved are calculated and discounted in the same way as to be consistent with the *Journal of Risk Analysis* article so that meaningful comparisons can be made.

6.4.4 Partial Sprinkler System Calculations

Local jurisdictions have the choice to adopt the full NFPA sprinkler code or a partial sprinkler code. The municipal model can be modified to determine the effect of installation of a partial sprinkler system. As is shown in Table 6-4, a large fraction of fires start in the kitchen, bedroom, and living rooms of a home.

Data provided by NFPA on leading areas of origin of home fires from 1989-1993 reveal that the three leading areas of origin are the kitchen, bedrooms, and living rooms, family rooms, or dens [Hall, 1994]. The rank order changes in terms of what percentage of civilian fire deaths, injuries, and amount of property damage result from fires that originate in these rooms.

Table 6- 4. Leading Areas Of Origin, Home Fires 1989 - 1993

Area of Origin	Fire incidents number (%)	Civilian fire deaths (%)	Civilian fire injuries (%)	Direct property damage (%)
Living rooms	9.3 %	34.7 %	16.9 %	14.3 %
Bedrooms	13.2 %	27.4 %	25.5 %	17.5 %
Kitchens	29.6 %	15.4 %	31.0 %	14.9 %
Total Percent	52.1 %	77.1 %	73.4 %	46.7 %

The remainder of the fires occur in small percentages in areas such laundry rooms, heating and equipment rooms, garages, attics, bathrooms, closets, hallways, and dining rooms. Given the high percentages of fire incidents, deaths, injuries and direct property damage resulting from fires originating in these three main areas, the question of the cost-effectiveness of partial sprinkler systems arises.

The leading causes of home fires are cooking equipment, smoking materials, and incendiary and suspicious fires. Cooking equipment is the leading cause of fire incidents (21.7%). Heating equipment and incendiary or suspicious causes were the second and third leading causes of fire incidents responsible for 18.3% and 12.4% of fires, respectively. Cooking equipment was also the leading cause of civilian injuries (24.3%), followed by smoking materials (12.4%), children playing (12.1%), incendiary or suspicious causes (11.1%), and heating equipment (10.5%).

In terms of civilian deaths from fire, the leading cause is smoking materials (23.3%) followed by incendiary or suspicious causes (17.6%), heating equipment (14.0%), and children playing (10.1%). The leading cause of direct property damage is incendiary or suspicious causes (19.8%), followed by heating equipment (13.7%), and electrical distribution systems (12.9%).

Seventy-seven percent of fire deaths alone occur from fires that originated in one of these three areas. In order to test the cost-effectiveness of a partial sprinkler system, some assumptions about the potential for cost reductions must be made. In order to determine a lower bound for cost, a cost was determined as a fraction of the number of sprinkler heads needed for a partial system relative to a complete NFPA13 system. This is a conservative lower bound because costs cannot strictly be assessed as a function of number of sprinkler heads. Other system components such as control valves are still needed. An estimate was derived from a sprinkler layout for 2175 ft^2 single family house. This layout required 21 sprinkler heads for a code-complying system. Partial sprinkling of the kitchen, living, and bedroom areas requires eight sprinkler heads. In a partial system are 12 sprinklers are not installed that would have been placed as follows: 3 in hallways, 1 in the dining room, 1 in an enclosed porch, and 7 in the basement. This is a saving of 12/21 sprinklers heads. Assuming that all sprinkler heads cover the same average area, this is a saving of 57%. A cost reduction for installation cost is then applied.

The partial system saves 57% of the cost, but benefits are also reduced by 23% (death) to 53% (property damage). The partial system does not have much impact on the decision for mobile homes and only has impact for one region/community size for multi-family occupancies. Residential fire sprinklers for retrofit of multi-family dwellings as well as new and used one and two family dwellings never become cost-effective at a $110,000 per life-year level.

6.4.5 Water Department Calculations

Local water departments often assess fees for increasing the size of an existing tap or installing a new connection to the public water system. While not always meaning to charge for water that is on stand-by for fire protection systems, most departments have policies in place that have not been reviewed to address the residential fire sprinkler issue. Back-flow preventors and/or water meters each have a pressure drop of between 5-10 psi. This can be a double hit, for some residences, since, if a back-flow preventor is required, the increased pressure drop in the system may cause the need for a larger tie in or a pump. In areas mandating or considering mandating residential sprinklers, it is extremely important to get the local fire departments to talk with the local water departments.

6.5 Limitations of the Study

There are three limitations of this work that should be understood:

1. The model developed here is a municipal model, not a homeowner model, and therefore does not consider individual occupant factors directly.
2. Model uncertainty could be reduced by better national fire statistics, but currently there is no formal mandatory governmental procedure to ensure good numbers on these statistics. (Reporting of fire incidents is voluntary on the part of individual fire departments.) A more formalized procedure should be developed.

3. The model did not account for trade-offs between residential fire sprinklers and other fire mitigation strategies, such as fire department densities and building fire protection. While these tradeoffs can only be determined within a wide uncertainty band, the model can be used to bound the problem.

The benefits-costs model developed here was a municipal model. It did not consider occupant factors. Age is an important factor in who dies in fires and why. Preschool children (age 5 and under) and older adults (age 65 and over) account for a disproportionate number of fire deaths in homes. Fire death rates for adults 65 and older are nearly twice the national average. They are almost three times the national average for adults 75 and older, and more than four times the national average for those 85 and older. Preschool children had more than twice the death rate of the national average [Slayton and Miller, 1995].

Smoking and drinking are also factors, although the data are less clear. Drinking does not correlate with the fire death rate unless the drinking is at a level that would render the individual unable to respond to stimulus. Twenty-five percent of the fire deaths are from fires that started with smoking materials, but non-smokers are often victims of these fires as well.

Other considerations for a homeowner model potentially include property taxes on the value of the system, financing, insurance premium credits, resale value, and individual risk aversion or willingness to pay.

The model can be used to determine an order of magnitude estimate of the cost-effectiveness of a residential fire sprinkler system for an individual with a greater than average risk from fire. If the probability of death from fire is increased three-fold in the model, residential fire sprinklers then become an attractive fire mitigation strategy for multi-family homes as well as mobile homes. They are still costly for one and two family dwellings with the possible exception of very risk averse individuals.

Another way to gain insight into the benefits-costs of residential fire sprinkler systems is to let total installation cost vary parametrically to determine at what level of installation cost switchover in the decision of cost-effectiveness occurs. At an installation cost of 25% of the estimated value, the dollars per premature death averted for all mobile homes is less than $1M per premature death averted, in all regions and across all community sizes. The cost per premature death averted for multi-family occupancies ranges from less than one to a high of $3M dollars in the Northeast, South, and North Central regions across all community sizes. In the West, the peak cost is $5M for new and $7M for retrofit of a multi-family occupancy. One- and two-family dwellings range in cost from $1.2 to $7M, with peaks of $8M and $10M in the West for new and retrofit, respectively.

6.6 Conclusions

1. Fire mitigation strategies and resources in the United States should be targeted more towards the residential fire problem which accounts for a disproportionate number of the fire deaths, injuries, and property loss.
2. Widespread sprinkler legislation across all regions, community sizes, and house types may not be a good use of resources.
3. Residential fire sprinklers appear to be a good fire policy decision for new mobile homes and for all mobile homes in the South. Factory installation procedures could make sprinklers for new mobile homes an even more attractive option.
4. This study shows the cost of sprinklers in multi-family dwellings and/or one and two family dwellings; this information is valuable to risk averse individuals.
5. The more specific results obtained from a solid, unbiased policy analysis is crucial to aid decision-makers. All previous calculations of the benefits and costs of residential fire sprinkler systems used national average values and concluded that sprinklers were not cost-effective. These studies masked the important role residential sprinklers can play in mitigating mobile home fire deaths.

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THE ROLE OF UNCERTAINTY IN IMPROVING FIRE PROTECTION REGULATION

7. CONCLUSIONS AND RECOMMENDATIONS TO STAKEHOLDER GROUPS

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS TO STAKEHOLDER GROUPS

This chapter discusses the contributions of the dissertation, identifies the important stakeholders, and based on the insights from the dissertation, presents recommendations to the stakeholders. Section 7.1 summarizes each of the four major contributions. Section 7.2 identifies stakeholders of this work, and categorizes them into functional groups based on their role in the process of ensuring fire-safe buildings. Section 7.3 discusses how this work impacts each of the stakeholder groups and what each group needs to do in order to advance the process of incorporating uncertainty into decision making. Sections 7.4 and 7.5 recommend specific future research that should be undertaken.

7.1 Contributions of the Dissertation

This dissertation makes contributions in four main areas:

1) It furthers the understanding among stakeholders regarding the nature and sources of uncertainty in the field of fire-protection engineering by demonstrating the potential for design-acceptability switchover and by developing a taxonomy of uncertainties.
2) It suggests a quantitative methodology for the treatment of uncertainty in a performance-based design and begins to advance the community towards agreeing on how to conduct a performance-based design with uncertainty.

3) It contributes a case-study that applies the performance-based design process with uncertainty and demonstrates many important issues in evaluating a design.
4) It demonstrates how to incorporate uncertainty into benefit-cost studies of proposed fire-safety regulations and delineates insights that can be gained.

The first contribution promotes an understanding of the nature and sources of uncertainty, develops a common language among fire-safety professionals, and facilitates stakeholder discussions. Contributions to promoting an understanding of uncertainty in fire-safety engineering design includes demonstration of the potential for switchover in the acceptability of a design and the identification of seven barriers to determining and documenting a level of fire safety for a given project. The creation of a taxonomy is useful as a aid in understanding, identifying, and investigating uncertainties as a function of the steps in a fire safety-engineering calculation.

The second contribution is a generic methodology for the treatment of uncertainty in fire-safety engineering calculations. This methodology structures and quantifies many aspects of good engineering and policy analysis as applied to fire-safety engineering. The process developed is iterative and shows where effort should be made to treat complexity and where best-guess or average numbers can be used.

The third contribution is a demonstration of a case study. The case study shows the importance of a model that properly incorporates uncertainty over a traditional deterministic model. A model that handles the critical uncertainties is even more important as policymakers go to a performance-based design context.

The fourth contribution shows the value of properly incorporating variability and uncertainty in a cost-effectiveness and benefit-cost decision-making context. Through an evaluation of the cost-effectiveness of mandating residential fire sprinklers, the importance of including variability by discretizing important uncertain parameters is demonstrated. For the residential sprinkler problem, this was accomplished by discretizing national average values of fire statistics and costs by area of the country, community size, house type, and house age. This study shows that mandating residential fire sprinklers in new mobile homes can be cost-effective when compared to other residential life-saving options.

7.2 Stakeholders

The establishment of good fire-safety design procedures requires a collaborative effort on the part of many people who play a role in the conception, design, use, and maintenance of a building. These groups of people are referred to as stakeholder groups. Table 7-1 shows how fifteen different stakeholder groups that this work directly addresses can be categorized into functional groups based on the roles that they serve in the fire-safety design process.

Table 7-1 Categorization of Stakeholders into Functional Groups

Functional Group	Stakeholder Group
Stakeholders involved with building design and approval	- architects - design engineers - building owners - authorities having jurisdiction
Stakeholders involved with building construction and supply	- construction companies - equipment suppliers - manufacturers
Stakeholders who provide scientific data, statistical data, and tools	- researchers - model developers - insurance industry - fire service
Stakeholders involved in setting policy/ code development	- code developers - governmental bodies - insurance industry
Stakeholders who share the building risk	- building occupants - the public - building owners - fire service - insurance industry - design engineers

Categorization in one functional group does not preclude inclusion in additional functional groups. For example, if the building owner occupies the building upon completion, then the owner can be placed in both the functional group responsible for the design and approval of the building and in the functional group that is exposed to the building fire risk. Another example is the role of the fire service. They are subject to the performance of the building under fire conditions, and they participate in fire investigations and data collections necessary for improved code-development decisions and modeling and better understanding of the basic fire risk. Thus, the fire service can be a member of two additional stakeholder groups.

Classification of stakeholders into functional groups is not meant to draw hard lines between them, but to delineate major concerns, areas of responsibility, and recommendations. In an ideal system, all of the stakeholder groups would participate in a dialogue and exchange of information, risk perceptions, and values. This would provide directional guidance to members of other functional groups. Our code-making system is not currently optimized to do this.

7.2.1 Building Designers and Approval Authorities

The stakeholders involved with design and assessment/approval of buildings are typically architects, design engineers, building owners, and authorities having jurisdiction. This group sets the scope of the project, identifies goals, and establishes design objectives. These stakeholders often make complex decisions regarding fire-protection features as they consider the potential for property protection, life safety, injury mitigation, and business continuity. The stakeholders responsible for the building design and assessment are often working towards competing objectives. For example, low cost is often in conflict with a high level of safety. Progress in one direction such as installing fire sprinklers for increased fire safety may impede progress towards a competing objective such as designing an economical building. Furthermore, the perspective of the building owner, architect, and authority having jurisdiction may very well differ. These different perspectives may lead to different design choices. The goals of building owners and architects can include: 1) providing a certain minimum level of safety at the lowest cost; 2) comparing the increase in cost to the increase in safety when deciding on additional fire-safety strategies; or 3) maximizing design flexibility by finding a unique way to provide a specific level of safety.

7.2.2 Builders and Suppliers

Many stakeholders are involved with building construction, the manufacture of building systems, and the design/manufacture of building products and materials. The group includes the construction companies, companies that supply building materials, manufacturers of HVAC and other mechanical systems, and fire-protection equipment suppliers. This group also includes manufacturers of furniture and other goods. The products that they manufacture play a key role in the ignition and spread of fire, both the materials used and the construction of these products have a large impact on the outcome of a fire scenario.

7.2.3 Scientists, Statistical Data Analysts, and Tools Developers

The stakeholders who provide scientific data, calculation methodologies, and simulation tools are scientists, engineers, and toxicologists engaged in fire research and product development. Some of these stakeholders work on developing models that simulate the build-up and spread of heat and products of combustion in a building during a fire. Other researchers work to develop empirical measurements and better measurement techniques to quantify parameters such as heat release rates, rates of generation of products of combustion, and radiative fractions. These parameters are important inputs to fire simulation models.

7.2.4 Policy and Code Developers

Code-development organizations set acceptable levels of societal risk for fire in the process of constructing codes. Since there are no national codes, non-governmental bodies such as the National Fire Protection Association, the International Code Council, the Society of Fire Protection Engineers, and the insurance industry set codes and establish guidelines. They need information on how to specify performance-based requirements. The insurance industry sets a lot of fire policy in the U.S. as companies have their own fire-safety standards and require a given level of protection to qualify for certain coverage and/or certain rates.

7.2.5 People Exposed to Building Risk

People who live or work in a building share building risk. This includes: 1) the public who may come in or around the building; 2) the building owner who has a financial investment in the building; 3) firefighters who may enter the building during an emergency. It may also include the insurance industry who has a financial interest in the building and the design engineer who takes professional responsibility for the building fire-safety design.

7.3 Specific Contributions and Recommendations to Stakeholder Groups

In addition to the generalized contributions explained in Section 7.1, there are some specific contributions important to stakeholder groups. The following discussion and Table 7-2 summarize these contributions. Sections 7.3.1 – 7.3.5 provide specific recommendations to each stakeholder group.

The stakeholders involved with building design and approval benefit from the move towards a standardized process for evaluating performance-based designs. The design process will be better understood, more thoroughly documented, and less questioned and thus lead to an expedited design approval process. These stakeholders will be able to use the taxonomy to aid in identifying and addressing uncertainties in the process, and they will benefit from the case study that demonstrates the entire process.

Stakeholders involved with building construction and supply will benefit from having well-defined quantitative performance measures of their products. Using these measures, the performance of existing products can be determined and criteria for product improvements can be set. This will lead to the manufacture and sale of higher-quality, safer products.

Results from this dissertation can aid stakeholders who provide scientific data, statistical data, and tools to prioritize research agendas by focusing efforts on important decisions where attention to the level of complexity is needed.

This work benefits stakeholders involved in setting policy by providing insights that will lead to better building and fire regulations. Also, the methodology helps to quantify a level of safety for existing regulations. The case study provides a directed way to study impacts of, and sensitivity to; many design parameters such as design fires and performance criteria. Case-study applications will inform the policymakers as to what design parameters should be standardized and how to best achieve this.

Stakeholders who are exposed to building risk benefit from having safer buildings with a known level of risk. They also benefit from alternative fire-protection options that allow for innovative building components. The proposed process allows building users to have direct input on what constitutes an acceptable risk measure. The benefit-cost and cost-effectiveness work done in this dissertation demonstrates how individuals in specific regions and building types could benefit from residential fire sprinklers, something that a study using national average numbers could not reveal.

Table 7-2. Contributions to Stakeholder Groups

Functional Group	Taxonomy/Demonstration of Switchover	Methodology	Case Study	Benefit-Cost Study
Stakeholders involved with building design and approval	- way to focus discussions, establish scope, goals and objectives - common language - checklist of things to consider	- set procedure to follow -higher confidence - answers AHJ's concerns/ more able to get performance designs approved	- demonstration of PBD process with uncertainty - sensitivity to performance criteria	- example of how to treat uncertainty and variability in benefit cost decisions - value of a life; comparative analysis
Stakeholders involved with building construction and supply	- challenges builders and suppliers to think about societal issues such as equity and life-cycle performance	- way to demonstrate performance of products; building components and systems	- demonstration of performance of building components and furnishings	-benefits and costs of residential fire sprinklers - motivation for governmental bodies to study construction related trade-offs vs. sprinkler systems
Stakeholders who provide scientific data, statistical data and tools	- need to quantify scientific uncertainties in the tools - begin to think about incorporating uncertainty in tools	- correlational analysis for prioritizing better data for inputs - points way for improvements to structure of models	- prioritize research agenda - demonstrates need for more comprehensive fire statistics	- Demonstrates need for more comprehensive and more available national fire statistics - usefulness tools that allow for indexed calculations and integrated treatment of uncertainty
Stakeholders involved in setting policy/ code development	- indicate problems with current performance-based design process	- directed way to study impacts of various ways to write code provisions - assertion	- demonstrates sensitivity to various numerical values	- benefits and costs of residential fire sprinkler mandate - template for evaluation of fire safety regulations
Stakeholders who share the building risk	- common language to discuss acceptable risk	- risks more explicit and thus open for public debate	- need to account for human behavioral aspects	- indication of fire risk vs. other risks - decision making for homeowner risks

7.3.1 Recommendations to Stakeholders Involved with Design and Acceptance/Approval

It is recommended that stakeholders involved with design and approval begin to incorporate systematically uncertainty in their evaluation of performance-based designs. A full uncertainty analysis may yet be impractical; however, incorporation of many of the insights from this work is practical. For example, the correlational analysis conducted determined the importance of uncertainty and variability in each of the input parameters. Results showed that input parameters for ventilation, rate of growth of the fire, and rates of production of products of combustion were strong predictors of key outcome criteria such as upperlayer temperature, concentrations of toxic gases, and time to flashover. Uncertainty in these crucial input parameters should be treated quantitatively in all design evaluations.

To aid design engineers in appropriately selecting ranges of values, shared database of values of rates of production for various products of combustion should be developed. Changes in rates of production with changes in burning characteristics should be documented in the database.

Standardization of design specifications such as tenability criteria, threshold values, and time to untenability would aid stakeholders involved with the design and approval of buildings. Individual performance designs would be allowed to meet these criteria; however, policy would set the criteria for each class of building type and occupancy. Architects, design engineers, and AHJ's should lobby for such modifications to the performance-based design process.

Building on the taxonomy presented in Chapter 2, this group of stakeholders should consider issues of life-cycle use, safety, and equity; and the incorporation of societal values and risk perceptions. Discussions between the different stakeholder groups are needed to establish the scope, goals and objectives of each project.

Selecting design fires and developing of design-fire scenarios should be standardized within the design community. The methodology for generating design-fire scenarios should include a process for modeling more realistic fires (e.g., smoldering fires and flaming fires with a slower initial growth rate).

In this dissertation, the benefits of systematically comparing each candidate design to a base-case design have been demonstrated. Stakeholders involved with the design and approval of a building should make this part of their standard practice. Finally, advice from this group should be integrated into the process of selecting additional case studies.

This functional group needs to provide input and maintain communication with stakeholders who provide scientific data, statistical data, and tools so that elements of model development can be prioritized.

7.3.2 Recommendations to Stakeholders Involved with Building Construction and Supply

Standardization of design specifications such as tenability criteria, threshold values, and time to untenability make investment in innovative technologies more cost effective for manufacturers of building components, equipment and supplies. These stakeholders must have a set of design targets in order to test their products and justify investments in research and product development. Also, these stakeholders must have the tools necessary to quantify increases in performance to enable sales and implementation of these innovative products.

Builders and suppliers should lobby for standardization of elements of the performance-based design that then become design criteria (e.g., establishing set probabilistic statements of performance for various building types and occupancy groups). These stakeholders also need to provide information to the policymakers who would enable the establishment of design specifications that are informed by the state-of-the-art techniques and analysis.

Members of this functional group should have input into the performance-based design process in order to ensure that building- and fire-simulation tools are constructed with the level of detail necessary for evaluating building components in real-world evaluations. For example, CFAST has been modified to enable modeling of wall assemblies composed of up to three different materials.

7.3.3 Recommendations to Stakeholders who Provide Scientific Data, Statistical Data and Simulation Tools

This functional group can and should make many contributions to improving the quantitative tools available to support performance-based designs, increasing the extent and availability of scientific data and statistics for use in modeling, and furthering the methodology used to treat uncertainty quantitatively. A five broadly stated tasks relative to each of these goals are discussed here. The Building and Fire Research Laboratory at the U.S. National Institute of Standards and Technology is a governmental research body that should play a key role in each of these tasks. Specific items that should be addressed by the government are discussed in Section 7.4.

For the quantitative treatment of uncertainty, a large number of design-fire scenarios need to be run. Thus, to aid in their use as design tools, high priority should be given to improving the run times of enclosure zone fire models and/or developing a reduced-form model.

Model developers should optimize code with end users in mind, incorporating modules that aid the user in the representation of key input parameters (e.g., rates of production of the various products of combustion). Currently, the user must do extensive research for each design conducted and make educated guesses as to how to best represent these input parameters. Many of the decisions that the designer must make for each simulation are outside of his or her area of expertise. Also, it is known that rates of production of the various products of combustion change with changes to the burning characteristics (e.g., vitiated fire environments and post-flashover conditions). The model should adjust the specified rates of production of products of combustion with changes in burning characteristics in the compartment, and guidance should be provided on extrapolating bench-scale data.

Life-safety is often a major goal of a fire-safety engineering design, and toxicity issues are fundamental to the ultimate goal of judging the acceptability of a design. The fire-safety community must develop a clear understanding of the production of toxic products of combustion and the levels of safe exposure for sub-populations, and they must have standardized methods for calculating time to incapacitation and death from toxic gases. Toxicity tests more specific to fire conditions must be conducted (including LC 1's, shorter timeframes, and the determination of distributions of threshold values). There is also a need to standardize methodologies for calculating the fractional effective dose, and the combined effects of exposure to toxic gases and elevated temperatures should be studied and quantified.

A building is designed to serve multiple purposes and has many components. A rigorous design procedure (with accompanying modeling tools) that optimizes performance across multiple systems should be developed. Such a design support system would be able to measure the effects of, for example, a change in wall material on fire protection, heat, light, energy use, and durability of the building.

Finally, good statistics are key to realistic modeling and policy setting. Comprehensive, accurate national fire statistics should be collected and made publicly available in a searchable database format.

7.3.4 Recommendations to Stakeholders Involved in Setting Policy and Code Development

Based on the results of multiple case studies, and with input from the other stakeholder groups, code developers and other policymakers should evaluate the potential for the regulation of some or all of the four parts of the probabilistic statement of performance. This would involve the establishment of design criteria and threshold values for tenability, the time required for safe egress, and the acceptable level of certainty. Regulation of the design criteria would aid in providing for equity among stakeholders, protect stakeholders who share building risk, and stimulate innovation among stakeholders involved with building construction and manufacture.

Integration of computer fire models and fire-safety codes and standards is needed. To initiate this process, stakeholders involved with setting policy should conduct an engineering review of current fire models to determine what is needed to enable construction and equipment trade-offs to be modeled accurately.

Stakeholders involved in policy and code development should further investigate means of mandating fire sprinklers in new mobile homes, particularly at the manufacturing stage.

7.3.5 Recommendations to Stakeholders Who Share in the Building Risk

Stakeholders who share the building risk should become informed end-users of buildings. This involves learning to take appropriate actions during a fire. It is also important that stakeholders who share building risk participate in the performance-based design process by making their values known. Finally, education is needed for all stakeholder groups on how to interpret risk and uncertainty concepts in fire safety.

7.4 GOVERNMENT INVESTMENT

The Building and Fire Research Laboratory (BRFL) at the National Institute of Standards and Technology (NIST) (i.e., the government) should fund work in this area over the next five years because they are uniquely suited to do so. They are the authors and keepers of the models and the basic science that underlies them. Relatively small investments in these areas would provide a stimulus for all of BFRL's customers.

1. Additional simulations should be conducted for this case study.

Using the same layout as this case study the follow-on simulations should incorporate lessons learned from the dissertation including:

Adding a wider range of fire types including non-flaming/smoldering fires and ventilation controlled post-flashover fires.

Smoldering fires occur when an object is heated sufficiently to decompose, for example, ignition of fabric from a lighted cigarette. If the fires does not transition to flaming, build up of the hazard is slow, on the order of several hours. Such fires produce high yields of irritant smoke, however, and the main risk is to sleeping occupants in highly compartmented spaces such as houses. Smoldering fires produce very little heat but generate toxic products of combustion and are important to determining death risk.

Conditions within the fire enclosure are likely to be lethal due to heat and toxic smoke before flashover occurs, but the main concern from flashed-over fires is the situation in the remainder of the building. Very large amounts of hot, toxic smoke are produced during the post-flashover stage. Two factors contribute to this phenomenon. At flashover, there is a sharp increase in CO yield (kg CO/kg fuel loss) and a very rapid rise in the production rate of CO due to the increased mass loss rate of the fuel. The increase in yield of CO during the post-flashover stage of the fire was not modeled for this case study because currently, CFAST does not allow the user the options of specifying an increased CO yield after flashover.

Modeling of HCN production.

Besides carbon monoxide, the most important toxic gas in fires is hydrogen cyanide, which is a potent asphyxiant. Hydrogen cyanide is released in any fire involving nitrogen. These include many common materials used in upholstered furniture and bedding (e.g., acrylic fabrics, fire retarded cotton fabrics, nylon, wool, polyurethane foam). Some untreated materials (e.g., wood, paper, cotton fabrics) are not sources of cyanide in fires. Most domestic fires involve mixed materials and thus, produce varying levels of cyanide depending on the main items involved and the fire conditions.

Correlating fire growth rates with room of fire origin.

This recommendation is an increase in the level of detail of the model. In the dissertation, both the design fires' growth rates and rooms of origin were statistically varied independently based on data from NFPA fire statistics for residential apartment occupancies. It is suggested that these two input parameters be correlated in order to produce a distribution of design fire scenarios that is even more representative. For example, an ultra-fast fire is statistically more likely to occur in the living room or bedroom than in the bathroom or entranceway.

Coupling fire growth rate and the radiative fraction

These variables should be correlated in the input scenario generator, also, additional scientific study is warranted as little information is known and even less is readily available in the literature.

2. Additional case studies should be conducted for different building types and geometries including commercial and industrial structures.

Additional case studies on a range of building geometries and occupancy types should be conducted to increase our understanding of the effects of various performance criteria and design fires. Additionally, such a collection of case studies could be used to construct a library of input modules that could be used in future design evaluations.

Additional case studies would substantiate uncertainty importance of each of the input parameters. For example, for these simulations, none of the input parameters to the weather module was statistically significantly correlated to predictions of the key outcome criteria. In order to determine more fully the importance of uncertainty in these input parameters, additional case studies should evaluate weather and test for extremes in weather conditions.

Uncertainty importance of input parameters for various types of building types could be used to simplify the process of evaluating performance-based designs by identifying the critical input variable set. Only inputs with uncertainty crucial to the prediction of the key outcome criteria would be treated as uncertain in future analyses.

3. Additional applications of the methodology

It should be demonstrated how the methodology for the quantitative treatment of uncertainty presented in Chapter 3 would be applied to other fire-safety engineering calculations such as the time needed to egress and the time to activation of fire-protection devices. In additional, use of the methodology to evaluate fire-safety goals beyond life-safety should be investigated. These might include providing for structural integrity of the building, limiting property damage, or documenting performance of individual systems or components.

4. Funding of model development

NIST is the provider of two state-of-the-art models for fire simulations, the computer zone model, CFAST, and the computational fluid dynamics model, FDS. Each of these models serves a unique function and both models are widely used both in the United States and internationally to conduct and verify performance-based fire-safety designs. NIST should invest in further development of these models.

In particular, a project should be initiated to improve run times for CFAST. An evaluation is needed to determine why such great variation in run times occurs and what adjustments may be made. Also, NIST should evaluate the potential to develop a reduced-form fire-simulation model.

NIST should assist the design community in establishing a database of rates of generation of products of combustion for various materials, including changes in these rates with burning conditions such as ventilation-limited and post-flashover stages of the fire. A good physical model for products of combustion is needed along with studies of the effects of scaling of bench-scale data for use in design simulations. Models should be adapted to allow for changes in rates of production of products of combustion with these changes in burning characteristics of the fire in the room.

Deterministic fire models should incorporate uncertainty in the major input parameters directly. Examples are the two inputs shown to be most highly correlated with output predictions, fire size and ventilation. A reduced-form or simplified, quicker run-time model could be developed that iteratively calculates key outcome criteria such as upper-layer temperature based on various potential openings of door and windows. The scientific community should develop methods to account for scientific uncertainties in the models and should fully document uncertainties in the physics and their implications to the designer, approval authority, and other stakeholder groups.

7.5 OTHER SPECIFIC (DISSERTATION-LENGTH) RESEARCH PROJECTS

1. Cost-benefit analysis of performance-based building and fire codes

If fire protection costs are only approximately 1-2% of total construction costs, can we really save enough money to justify performance codes? This research would look at other potential sources of savings such as changes in construction industry practices leading to expansion and increased efficiency, savings in manufacturing, stimulation of the economy by allowing for and encouraging innovation, and savings due to increased design flexibility.

2. Validation of safety of prescriptive-codes and justification of performance-regulations in terms of safety to life

Just as it would be a non-trivial exercise to justify performance-based building and fire-safety regulations on cost-savings, it would be even more challenging to justify them on potential savings to life. We don't know how safe the prescriptive codes are; however, we do know that under the current prescriptive-code system, there is a low life loss in non-residential settings. Can we validate prescriptive codes in terms of safety? Can we justify performance codes in terms of loss of life?

3. Quantitative treatment of scientific uncertainties

There is a need for a methodology to quantify scientific uncertainties. This methodology would need to be based on either (or both) validation studies and scientific evaluation of individual phenomena.

4. **U.S. national building and fire code: Local vs. Regulatory standards; Prescriptive vs. Performance**

This project would theorize a regulatory system very different from the existing system of voluntary consensus-based fire codes. It would evaluate the usefulness of a nationally mandated building and fire code by benchmarking with what other countries do.

5. **Reliability vs. Cost of residential fire sprinklers**

There is no doubt that residential fire sprinklers can and do save lives. However, as was shown in Chapter 6 of this work, installation of residential fire sprinklers according to current standards can be quite expensive. This study would evaluate the potential for less expensive residential fire-sprinkler systems that could enjoy more widespread installation. These might deviate from current installations in terms of connections to domestic water supplies, types of piping used, pressure and flow requirements, and/or hardware requirements. Quantification of any reductions in reliability of these systems would have to be made and incorporated into the evaluation.

7.6 Conclusions

This study has demonstrated numerous ways in which the quantitative treatment of variability and uncertainty can lead to improved fire-protection regulations. It begins a process of moving forward towards establishing design criteria, code language, and research programs focused on the goal of ensuring fire-safe buildings.